

1995

## Constructed Wetland Design Criteria : A Study of Their Role in Contaminant Removal From Urban Stormwater Runoff

A. J. Braid  
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# **Constructed Wetland Design Criteria**

**A Study of Their Role in Contaminant Removal from Urban  
Stormwater Runoff**

**by**

**A.J.Braid**

*A Thesis Submitted in Partial Fulfilment of the Requirements for the  
Award of:*

*Bachelor of Science (Environmental Management) - Honours  
at the Faculty of Science, Technology and Engineering, Edith Cowan  
University.*

**Date of Submission: 10<sup>th</sup> November 1995**

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# Abstract

This study was conducted to review effective design criteria for constructed wetlands treating urban stormwater and to assess the design features of local constructed wetlands in relation to the theoretically ideal design features. The study was generated out of Water Authority of Western Australia (WAWA) concern that existing inconsistent design criteria may result in constructed wetlands not meeting contaminant removal objectives. Three components to the study involved: design criteria compiled from a critical review of relevant literature, field assessment of selected sites with significant differences in design, and a design critique of those sites based on the compiled design criteria. The sites selected were Bartram Road and Hird Road wetlands on the South Jandakot Drainage Scheme and Russell Street wetland on the Bayswater Main Drain, all in the Perth Metropolitan area.

Reporting of current constructed wetlands in journal literature was limited and the projects that were published reported widely ranging designs and performances. There was not a single constructed wetland project reviewed that satisfied all of the design criteria and this was concluded to be the major contributing factor to the reported inconsistent performances of constructed wetland systems.

Assessment of flow regimes at the wetland sites using fluorometer analysis of Rhodamine WT tracer dye showed that the flow path in each of the wetlands was short-circuited, significantly reducing theoretical residence times. At Bartram Road it was reduced by a factor of four and at Hird Road by a factor of six. Inadequate storage at Russell Street resulted in a residence time of less than a day.

Performance evaluation at each wetland analysing the difference between import nutrient loads and export loads over a three day period showed that none of the wetlands met their design phosphorus removal objectives for the study period. All sites exported net Total Phosphorus (TP) and Bartram Road was the only site to retain net Total Nitrogen. There was a dramatic variation in daily contaminant removal efficiency at all sites where for example TP removal at Bartram ranged from -95% to +31% over the three days.

Given that the design critique revealed significant flaws in the individual design criteria the poor performance of the study site wetlands was not surprising. The study concludes that there is effective design criteria for contaminant removal from stormwater. However, it is not being implemented as accepted practice. For this reason it is recommended that the stormwater management agencies formalise the design criteria researched in this study and persist with constructed wetlands as a stormwater treatment strategy.

# Declaration

I certify that this thesis does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any institution of higher education; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

Signature ....



Date..... *23.1.96* .....

# Acknowledgements

I wish to express my appreciation to the people who gave me guidance, assistance and support throughout this project. Thanks to;

my supervisor Dr Paul Lavery whose unfailing enthusiasm was an inspiration,

the science, technology and engineering laboratory staff at Joondalup Campus of ECU,

the marine & fresh water laboratory staff at Murdoch University,

officers of the WAWA, Jeff Kite, Paula Duncan and Alan Dean,

Mr. Eddy Sruzynski of Hammond Road Jandakot for granting entry permission to the Hird Road wetland as well as providing valuable anecdotal history of the area and

finally to my wife Patricia for her support, understanding and tolerance without which this thesis would not have happened.

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## **Chapter 1**

# **Introduction**

### *The background, significance and purpose of the study*

#### ***Background to the Study***

Traditional methods of stormwater management treated runoff as waste to be disposed of quickly and cheaply. The basic engineering systems designed to achieve runoff disposal involved either discharge to recharge basins or directly to natural waterbodies. Direct discharge to natural water bodies is a significant source of pollution, both as contaminant loading and alteration to natural hydrological regimes. Environmental protection agencies and an environmentally aware public no longer tolerate this method of disposal. Consequently, alternative stormwater management strategies have developed.

The use of constructed wetlands to treat urban stormwater is one such strategy. This is an option that has the potential to provide water quality improvement, flood mitigation and replacement of lost wetland habitat. The observed ability of natural wetlands to act as water purifiers in riverine flood plains led to the development wetlands to treat wastewater (sewage) in America and Europe (Livingston, 1989; Mitsch & Gosselink, 1993; Silverman, 1989). The knowledge compiled from the use of constructed wetlands to treat wastewater was subsequently adopted by stormwater managers in the USA (Mitsch, 1993). This trend to mimic natural systems in the management of urban stormwater is being followed in Australia (O'Loughlin, Young & Molloy, 1992).

The Water Authority of Western Australia (WAWA), the State Government agency currently responsible with managing wetlands and the strategy for urban stormwater management, is incorporating constructed wetlands into strategic drainage plans to reduce the pollution from stormwater runoff to receiving environments. Local Government Authorities and property developers are also incorporating constructed wetlands into local drainage schemes as part of water sensitive urban design (Australian Environment Council, 1988; O'Loughlin et al., 1992; Mouritz, 1994; Whelans & Halpern Glick Maunsell, 1993). However, in all cases, the constructed wetland design contains unknown elements that may affect their viability and sustainability as alternative treatment strategies. Research into the use of wetlands for this purpose has tended to rely on performance evaluation of constructed

wetlands (Kusler & Kentula, 1990). This 'trial and error' approach has resulted in many failures, including the formation of eutrophic ponds or simply poor performance of wetlands designed to reduce pollutant loads to receiving waters.

Literature reporting the design, use and performance of constructed wetlands for stormwater treatment describe an inconsistent approach to design and a lack of data on successful performance evaluation (Kentula et al., 1993). This inconsistent design approach applies to constructed wetlands for the treatment of urban stormwater in the Perth metropolitan area. The WAWA became concerned that the inconsistent design of treatment wetlands may be producing constructed wetlands that were not meeting performance design objectives.

Two districts in which the WAWA has recently constructed wetlands for stormwater treatment are Jandakot and Bayswater. The Bartram Road Buffer Lakes are an integral part of the South Jandakot Drainage Scheme serving the stormwater treatment requirements of the newly developed Jandakot urban area. A second wetland system in the same district utilises a degraded natural wetland area at Hird Road to treat stormwater runoff from adjacent urban development. The Bayswater constructed wetlands are located on branches of the Bayswater Main Drain which discharges runoff from the Bayswater-Morley catchments to the Swan River. Russell Street and Mooney Road are two pre-existing compensating basins converted to wetland systems on the Bayswater Main Drain as part of the WAWA treatment strategy.

There was particular concern in the poor performance of the Bartram Road Buffer Lakes in that the analysis of stormwater nutrient concentrations at inlet and outlet stations to the system showed no significant difference in concentration over an annual sampling period. This constructed wetland was built with the specific purpose of protecting the Beeliar Wetland Chain from stormwater pollution generated by the recently developed South Jandakot Urban district. This project grew out of that concern and was designed to determine what are effective constructed wetland design criteria.

## ***Objectives of the Study***

The principal objective of this study was to determine appropriate constructed wetland design criteria for sustained effective contaminant removal from urban stormwater runoff. The secondary objective was to

recommend management action to improve the performance of the Bartram Road, Hird Road and Russell Street constructed wetland systems. The research questions formulated to meet those objectives were:

1. What are the properties of stormwater that are considered to be pollutants,
2. Why are wetlands a viable option in the treatment of stormwater pollution,
3. What are the functions of wetlands that remove pollutants from the waterbody,
4. How are these functions mimicked in constructed wetland systems,
5. Do the local constructed wetland projects have the required wetland elements to perform effective contaminant removal; if not what changes can made to improve their contaminant removal efficiency,
6. What defines a constructed wetland and what is effective contaminant removal.

### **Terminology**

The last research question posed needs to be addressed at this point to avoid confusion between a variety of wetland terms used synonymously. Constructed wetlands, contaminant removal efficiency and wetland vegetation are such terms requiring clarification for interpretation of this thesis.

### ***Constructed Wetlands***

Despite considerable scientific, management and legal debate, no one definition of wetlands has achieved universal acceptance (Balla, 1995; Hammer, 1992; Lewis, 1990; Mitsch & Gosselink, 1993). An in depth critique of the debate is beyond the scope of this report, however it is necessary to adopt terminology for understanding of this report.

Here the Ramsar Convention (1971) definition is considered to have the necessary width to encompass all wetland structures (Balla, 1995; Mitsch & Gosselink, 1993);

*“... a wetland is any area of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt including areas of marine water, the depth of which at low tide does not exceed six metres...”*



A distinction between natural and non-natural wetlands is important for design, management and regulatory control (Fields, 1993; Hopkins & Argue, 1992; Livingston, 1989). This report accepts the distinction between natural and non-natural wetlands made by Balla (1995) in *Wetlands of the Swan Coastal Plain; Volume 1*.

Thus, non-natural wetlands are:

*“.....bodies of water in an area that previously did not contain a wetland or where the nature of the wetland has been significantly altered by artificial means.”*

The proliferation of non-natural wetland systems as either pollution control, wetland loss mitigation or landscape enhancement has spawned a milieu of terminology to describe them. Terms such as constructed, artificial, created, and rehabilitated wetlands, buffer lakes or biological filters are synonymous in their use. The principal design objective of the wetland presents terminology that avoids ambiguity (Hammer, 1992) such that constructed wetlands are:

*“.....those wetlands intentionally created from non-wetland sites for the sole purpose of wastewater or stormwater treatment.” while created wetlands are “ ...those intentionally created from non-wetland sites to produce or replace natural habitat.”*

### ***Contaminant Removal Efficiency***

There are two distinct methods of describing contaminant removal efficiency (CRE); the first as a percentage reduction in outflow concentration of the element compared with the inflow concentration; the second as a percentage of load retained compared to total input load to the wetland. Both are legitimate measures, however they present different aspects of effectiveness.

The decision to use either percentage reduction in concentration of the effluent or percentage of load retained within the wetland will depend on the CRE objective of the wetland design. Where the objective is simply to meet an effluent concentration limit, the percentage concentration CRE is the most useful measure. However, where protection of the receiving environment from chronic, long term loading is the objective, percentage load CRE is more appropriate.

### ***Wetland Vegetation***

Terminology applied to vegetation within wetland systems attempts to distinguish species as terrestrial, semi-terrestrial, shallow or deep water dependent. The tolerance range of species occurring in wetland habitats has presented difficulties in assigning a finite category to particular plant species. It is therefore preferable to include all the above categories as wetland vegetation. Hammer (1992) defines such wetland plants as:

*“...plants capable of growing in an environment that is periodically but continuously inundated for more than five days during the growing season.”*

The advantage of grouping plants in this manner assigns a consideration to both woody and herbaceous plants that form part of the wetland ecosystem. The disadvantage in accepting this definition is that buffer vegetation that may never be flooded but is an integral part of the system is omitted. The definition is not particularly useful beyond the narrow scope of constructed wetlands for nutrient stripping.

### ***Scope of the Study***

To answer research questions 1-4 (p4.) this study prepared a critical review of the literature focussing on studies of constructed wetlands for the treatment of urban stormwater runoff. This review constituted a major component of the research project and the findings are presented in Chapter 2.

Research question 5 required field assessments of existing local constructed wetland projects to determine their design effectiveness and compliance with the effective design criteria established by the literature review. The field assessments comprised flow regime trials, compliance auditing through site mapping and determination of contaminant removal efficiency and nutrient storage in a range of local wetlands of differing design. In all of the chapters 2, 3 & 4 the structure will focus around a comparison of the three different wetlands, which display increasing levels of design complexity.

A critique of the selected wetlands design is conducted as part of the literature review (chapter 2). The flow regimes of the constructed wetland systems were conducted using Rhodamine WT tracer dye and the process and results of these trials are discussed in chapter 3. The determination of wetland nutrient retention is presented in chapter 4.

The implications of the findings of the research project to future use of the constructed wetland strategy are discussed in the concluding chapter.

## **The Study Sites**

Three sites selected for field assessment and design criteria comparison represented vastly different approaches to the constructed wetland strategy. The history of the sites (Bartram Road, Hird Road and Russell Street constructed wetland systems) are outlined here and described in detail in the case study section of chapter 2. The physical parameters and site maps of the constructed wetland systems are presented in chapter 4.

Bartram Road Buffer Lakes are located in the Jandakot district 40km south of Perth Central. They were developed in response to Environmental Protection Authority requirements to ensure the environmental quality of the Beeliar wetlands was not degraded as a result of the South Jandakot urban development. The rezoning of the South Jandakot area as urban was conditional on the lodgement and approval of the South Jandakot Drainage Management Plan and the Environmental Management Programme (EMP) for the South Jandakot Drainage Scheme (G B Hill & Partners Pty Ltd, 1990; 1991). One of the conditions of the EMP was that the constructed wetland achieve a 15-30% reduction of phosphorus load in the runoff effluent. Management action is required when the performance drops below a 15% reduction in phosphorus loads. Evaluations of performance for 1993 and 1994 show that there has been no significant difference in inflow and outflow nutrient concentrations during that time (Technical Review Committee, 1994; Fuller & Deane, 1995). This constructed wetland system is the focus of WAWA concern and is the most complex in design. The system features five cells whose functions range from settlement ponds, pollutant entrapment and transformation to storage for flow attenuation.

Hird Road Buffer Lakes are also in the Jandakot District and are approximately 3km north of the Bartram Road system. The Hird Road system consists mainly of a degraded natural wetland and treats stormwater from a recent urban housing development. This project fell under the umbrella of the South Jandakot Drainage Scheme but did not have the same public consultation as did the Bartram Road system. The selection of the site for this study was to provide a comparison with essentially natural wetland functions.

The Russell Street Biofilter is located in the Morley district approximately 10km north-east of Perth central. The Russell Street system was selected as one of two existing drainage compensating basins on the Bayswater Main Drain to be converted to wetland filters. Funded from the Prime Minister's 1992 "One Nation Statement" the Russell Street project was designed to "...*demonstrate the effectiveness of new and innovative Australian technology.*" (W G Martinick & Associates, 1994). This site represented the simplest design. It is essentially a single cell, square compensating basin with minor planting and bathometric alterations.

### ***Significance of the Study***

The Jandakot and Bayswater constructed wetland systems have adopted significantly different design criteria but have similar contaminant removal objectives. The field assessment of the different design criteria adopted by the study sites enabled a comparison between the sites and the compiled optimum design criteria. This information is of immediate benefit to the WAWA in ensuring their compliance with the requirements of the EMP for the South Jandakot Drainage Scheme. In addition the research will assist with determining future policy for managing agencies on the use of constructed wetlands to treat urban stormwater pollution.

## **Chapter 2**

# **Literature Review**

## ***Stormwater as a pollutant and constructed wetlands as a treatment strategy.***

### ***Purpose and Scope of the Review***

Constructed wetland systems for the treatment of stormwater pollution became a popular management strategy in the late 1980's. As alluded to in the introduction, the strategy arose from the successful use of wetlands in the secondary treatment of wastewater, an awareness of stormwater as a pollutant and a awareness of the need for a holistic approach to maintain environmental quality. The strategy was implemented largely on theoretical concepts generated by research into natural wetland systems but with little specific research into the essential elements that enable contaminant removal (Livingston, 1989). Understandably, these initial projects experienced teething problems and reported mixed success rates.

A preliminary review of literature on constructed wetland systems reflected that variability in effective performance. Examples existed in Californian systems at Lake Tahoe (Reuter et al., 1991) and at Fremont (Meiorin, 1989) where CRE was negative for ortho-phosphates and ranged from +80 to -90% for nitrates. At these sites the researchers identified the cause of performance variation as high runoff volumes generated by intense storm events by-passing the treatment system. Australian constructed wetland systems at La Trobe University (Graham, 1991) and in the Blue Mountains of NSW (Swanson, 1992) reported nutrient CRE that ranged from 50% to 95%. The data was compiled on monitoring the CRE in fewer storm events than those in California but they also noted variations in CRE related to intensity of storm events.

Further research into wetlands found that the hydrological cycle was the major determinant of wetland function, influencing both the nutrient cycle and nutrient availability (Mitsch et al., 1993; Richardson & Craft, 1993). Studies into hydrological cycles of constructed wetlands found that the theoretical concepts of flow behaviour were seldom replicated in field situations (Kadlec et al., 1993; Pilgrim et al., 1992). Reviews on these problems identified the need for an integrated and multi-discipline approach to the design and construction of wetland projects (Wetzel, 1993; Wilcox, 1988).

This review is structured to represent an integrated approach to the design of constructed wetlands. It commences with the identification of stormwater as a pollutant and determines what pollutants are likely to present in the runoff. Following the characterisation of stormwater, strategies for the treatment are discussed. Within an integrated catchment management approach the use of constructed wetlands appears to be a viable option. The review then examines the various functions of wetland systems that enable pollutant removal from the waterbody. The next step was to match the various functions of wetlands to the project objectives. A synthesis of design elements was produced and includes options that match particular pollutant removal requirements. Case studies of the selected sites included a design critique based on the compiled design elements. Where applicable management action is recommended. The case study results support the design element compilation. The review concludes with a discussion of the future role of constructed wetland strategy in urban areas.

### ***Urban Stormwater Runoff as a Pollutant***

Uncontrolled urban stormwater runoff results in significant negative impacts on receiving environments. Such runoff is a direct consequence of the effects of urbanisation on natural hydrological cycles (Australian Environment Council, 1988). The reduced permeability of urbanised areas can result in runoff as high as ninety per cent above natural land uses. In addition, there is a reduction of fifty to ninety per cent in peak flow time compared to pre-urban regimes (O'Loughlin et al., 1992). The resultant high intensity, short duration flows have significant impacts on receiving environments, and a high potential to scour banks and stream bottoms. This altered hydrological regime significantly increases the potential to transport contaminants from the urban environment (Lawrence, 1995; O'Loughlin et al., 1992). American and Australian studies on urban runoff show an increase in average contaminant concentrations; heavy metals by thirty per cent, nutrients by five to ten per cent and suspended solids by ten per cent, compared to pre-urban conditions (O'Loughlin et al., 1992; Silverman, 1989). Environments receiving urban stormwater in this manner are unable to adapt to the increased loading rate, and as a result, undergo severe degradation.

With the improvement in pollution control from industrial point sources, urban stormwater represents a significant non-point source of pollution that requires active management to redress (Baker, 1993;

Lawrence, 1995; O'Loughlin et al., 1992). An understanding of the nature of urban stormwater runoff is essential for effective treatment planning.

### ***Nature of Urban Stormwater Runoff***

It is not possible to characterise urban stormwater runoff with a simple range of properties. Extensive studies of the urban runoff demonstrate highly variable between-catchment, between-event and within-event contaminant concentrations (Andoh, 1994; O'Loughlin et al., 1992). Variability arises from differences in catchment land use, contaminant availability, rainfall intensity and duration, and topography of the catchment. A summary of contaminant concentrations given in Table 2.1 illustrates this variability.

The current strategy in stormwater treatment is to capture the first flush event of runoff based on logic that the first flush contains the highest concentration of pollutants (O'Loughlin et al., 1992). In fact O'Loughlin et al. (1992) suggests that the highest contaminant transport will occur during peak flow periods, all else being equal because the rate of pollutant transport is primarily dependent on flow rate. Literature on stormwater runoff typically focuses on contaminant concentration levels. Peak flows have seldom been sampled thoroughly and this may result in underestimating total loads of runoff contaminants to receiving environments (Andoh, 1994; O'Loughlin et al., 1992). Even though estimates of runoff contaminant loadings may be underestimated the data in Table 2.1 indicate that they do present urban stormwater runoff as a significant non-point source of a variety of pollutants. What these features of stormwater runoff suggest is that the stochastic nature of rainfall and availability of contaminants makes contaminant loadings difficult to determine with any degree of certainty (Andoh, 1994). It is therefore necessary to allow for large variations in flow volumes and contaminant concentrations in the design of treatment systems and not focus on designs which are based on only a narrow range of flow events.

The discussion to this point has emphasised the stochastic nature of urban stormwater runoff. The contaminant loading contained in the runoff is a function of three variables. First is the availability of pollutants within the catchment. Second is the intensity and duration of rainfall events within respective catchments which determine the load carrying capacity of the runoff. Third is land use which determines the composition of the contaminant suite in the runoff and the permeability of the catchment.

Land usage is the critical element affecting the catchment runoff patterns (Deeley, 1993; Tan, 1991). Studies by Deeley (1993) on stream flow in the Swan, Avon, Canning River catchments demonstrated the direct relationship between land use and runoff characteristics. Shorter term studies by Tan (1991) on Perth metropolitan catchments also demonstrated that relationship. Figures displayed in Table 2.2 show significantly different proportions of dissolved to particulate form of nutrients that occur between catchments. Studies in other Australian states and in American studies demonstrated similar variability between catchments (Graham, 1991; Livingston, 1989).

Table 2.1. Variability in the nature of urban stormwater runoff.

Parameter	Australia	America	Bartram Road Catchment	Russell Street Catchment	Hird Road Catchment	Desirable urban stream quality
Suspended Solids	250 (50-800)	150 (2-2890)				< 25
Total Phosphorus	0.6 (0.1-3)	0.33 (0-4.3)	0.47 (0.21 - 0.81)	(0.04 - 0.23)	0.18 (0.1 - 0.30)	< 0.05
FRP(ortho-phosphate)	0.2 (0.05-0.5)	0.2 (0.05-0.5)	0.35 (0.12 - 0.67)	(0.01 - 0.12)	0.11 (0.01 - 0.20)	
Total Nitrogen	3.5 (2-6)	1.5 (0.34-20)	(1.54 - 3.36)	(0.37 - 1.07)	(1.27 - 2.67)	< 0.5
Total Kjeldahl Nitrogen	2.5 (1-5)		2.48 (1.54 - 3.32)	(0.35 - 0.91)	1.68 (1.03 - 1.99)	
Lead	0.25 (0.05-0.45)	0.14 (0.003-28)	(0 - 0.34)		(0 - 0.37)	< 0.025

Note. All measurements given are in mg/L, with the mean value followed by the range in parenthesis. The comparison between desirable stream limits and the concentration of contaminants recorded in the runoff demonstrates the need to treat urban stormwater runoff as a pollution source. The data was compiled from the following sources: Australian summary and desirable stream limits - Graham (cited in O'Loughlin et al., 1992) and AEC No.23 (1988); American - Livingston (1989); Russell Street - Tan (1991); Bartram and Hird Road - Fuller & Deane (1995), Dean, et al. (1994) and Technical Review Committee (1994).

This inter-catchment variability in the proportion of dissolved and particulate nutrients has significant implications for the design of nutrient stripping wetlands. This is simply because the functions of wetland systems which enable contaminant removal to occur are different for the two forms of nutrients. Thus, adequate characterisation of stormwater is an important first step in the design of constructed wetlands. Only then can the wetland functions which will remove either or both forms of nutrient be



incorporated into the specific design. The next section elaborates on these functions of wetland systems which result in contaminant removal from stormwater.

Table 2.2. The relationship between land use and the nature of stormwater runoff .

Catchment	N:P - range (mean)	% inorganic N	% SRP to TP	Catchment Land use	Source
Avon	40:1 to 7:1 (23:1)	24	13	rural	Deeley, 1993
Claisebrook	7:1 to 15:1 (11:1)	54	24	urban industrial	Deeley, 1993
Ellen Brook	4:1 to 2:1 (2.74)	17	60	rural	Deeley, 1993
Bartram Road	(6:1)	12	75	40% urban 60% rural	Dean et al. 1993
Hird Road	(17:1)	47	61	40% urban 60% rural	Dean et al. 1993
Bayswater	10:1 to 5:1 (8:1)	11	10	50% urban & commercial	Tan, 1991

Note. The nature of stormwater runoff is directly related to the catchment land use. The nitrogen to phosphorus ratio and the percentage of biologically available nutrients reflects both the different land use and the soil type of catchments.

### ***Appropriate Stormwater Management***

The contemporary strategy for maintenance of environmental quality is for zero pollution production (Geiger, 1992; Walesh, 1989). In accordance with that strategy, appropriate stormwater management attempts to mimic 'before development' hydrological regimes (Hammer, 1992; Livingston 1989). This involves treatment of runoff at the source to reduce runoff volume and contaminant transport. Such strategies include street sweeping programmes to reduce potential contaminant loads. In addition, increasing local infiltration through water harvesting techniques such as swales and depressions will reduce runoff volume (Ferlow, 1993; Whelans & Halpern Glick Maunsell, 1993).

However, source control devices are impracticable in catchments with steep grades. Steep or large catchments require within and end-of-line control devices. Within systems control devices include retention basins that can reduce sediment loads and attenuate peak flows. End of line treatment replaces the traditional discharge structures, with constructed wetlands becoming the favoured control device in many situations. Either as a within system or end-of-line treatment, a constructed wetland affords stormwater quality improvement and landscape enhancement (Evangelisti, 1994; Livingston, 1989; Whelans & Halpern Glick Maunsell, 1993).

Traditional stormwater management had as its objective the minimisation of social and economic cost due to flooding (O'Loughlin et al., 1992). The strategy to accomplish this objective involved 'hard' engineering solutions that channelled the runoff away from the urban areas as quickly and cheaply as possible (O'Loughlin et al., 1992; Walesh, 1989). The engineering solutions employed were effective in meeting the 'in situ' management objectives. However, neither the strategy nor the objectives recognised stormwater runoff as a significant pollution source and neither considered the impacts of the runoff on receiving environments. The result of the traditional stormwater management methods was to compound and relocate the impacts of runoff from the source to the discharge and its receiving environment. Unfortunately, the receiving environment was typically a natural system that could not adapt to the sudden influx of water or contaminants.

Constructed wetlands for the treatment of stormwater are a recent innovation. This usage derived from the use of constructed wetlands for wastewater treatment (Hammer, 1992; Mitsch & Gosselink, 1993; Mouritz, 1994). The research and development of constructed wetlands for wastewater treatment centred on a controlled hydrological cycle that included a 'steady state' of volume and contaminant concentration loadings (Brown & Reed, 1992; Knight et al., 1992). This is not the case with stormwater inflows. The stochastic or pulsing nature of stormwater runoff presents a significantly different hydrological cycle to that of wastewater. It is thought that the differences between the two treatments does not allow a direct transfer of knowledge and technology from one to the other.

Constructed wetland for stormwater treatment design needs to adopt water purifying functions of natural wetlands with similar hydrological cycles (Klunder, 1992; Kusler, 1990; Livingston, 1989; Mitsch, 1993; Silverman, 1989; Wilcox, 1988). The adoption of this type of treatment strategy requires a considerable change to the traditional philosophies of stormwater management. In addition current environmental quality awareness demands that a holistic approach be adopted, not only to the impacts of stormwater but also to the mitigation programmes.

Integrated Catchment Management (ICM) uses a holistic approach. Numerous articles and reviews, local, national and international, expound the virtues of ICM (Andoh, 1994; Australian Environment Council, 1988; Dodds et al., 1993; Geiger, 1992; Lawrence, 1995; Mouritz, 1994; O'Loughlin et al., 1992; Whelans & Halpern Glick Maunsell, 1993). However ICM is not a simple answer, it is a

complex process involving: diverse climate, urban development, environmental and social issues, and jurisdictional boundaries. Collett (cited in O'Loughlin et al., 1992) stated that ICM for urban areas must have the following objectives:

- “- to improve the urban environment and the quality of life;*
- to optimise energy and resource use in urban areas;*
- to minimise soil erosion and sedimentation, especially during the construction phase of development, by the application of appropriate control systems and;*
- to minimise adverse downstream effects of urban areas by the use of appropriate runoff management systems.”*

The use of constructed wetlands then becomes a vehicle to achieve the above objectives within the framework of ICM. It is essential that the use of constructed wetlands for the treatment of stormwater pollution be viewed as part of the solution and not as a 'cure all'.

## ***Contaminant Retention in Wetlands***

Natural wetlands in their numerous guises, provide flood attenuation and reduce contaminant loads of runoff or flood waters. Their proven ability to act as water purifiers provide stormwater and wastewater managers with a potentially effective and sustainable treatment system (Hammer & Bastian, 1989). However, research conducted into the structure and function of wetlands has been slow to permeate into the design of constructed wetlands (Hammer & Bastian, 1989; Mitsch 1993; Silverman 1989).

Extensive inventories on American usage of constructed wetlands for water quality improvement show minimal conformity or agreement on design elements (Brown & Reed, 1992; Knight et al., 1992). A review of design and performance criteria for constructed stormwater wetlands both nationally and internationally by Evangelisti (1994) supports this view.

Research into natural wetlands has established them as productive and highly valued ecosystems too valuable and fragile to risk as discharge areas for wastewater or stormwater effluent (Silverman 1989; Mitsch 1993; AEC, 1988). However research has tended not to examine the long term effects of their role as contaminant sinks (Wetzel, 1993; Wilcox, 1988).

Monitoring of constructed wetland systems shows they have a higher CRE than many natural wetlands (Table 2.3). However, research shows that the ability of wetland systems to strip contaminants is not limitless. Tables 2.3 & 2.4 give a summary of water quality improvements brought about through the

use of constructed wetlands for wastewater and stormwater treatment, and highlights the potential for improved water quality of stormwater runoff treatment in constructed wetland systems.

Table 2.3. Sediment and Phosphorus Retention in Wetlands.

Wetland Type	Sediments		Phosphorus	
	loading (Kg m <sup>-2</sup> yr <sup>-1</sup> )	% retention	loading (g m <sup>-2</sup> yr <sup>-1</sup> )	% retention
Natural Wetlands	150	3	8 - 80.2	4.5 - 10
Restored & Created Wetlands				
NPS Control	2.18 - 21.27	88 - 98	0.4 - 3.6	63 - 98
Wastewater surface flow	1.07 - 65.2	61 - 98	4.7 - 56	46 - 80
subsurface flow	15 - 58.8	49 - 89	131 - 631	8 - 89

Note. Source of data Table 17 - 3, Mitsch & Gosselink (1993). NPS = nonpoint source

Table 2.4. CRE for Constructed Wetlands in USA, Australia and England.

	% Load Retention as CRE		
	TSS Range	TP Range	TN Range
USA	32 - 91	7 - 90	5 - 85
England	56	21	
Australia	62 - 96	30 - 95	38 - 76

Note. Variations in the ranges reflect the number of wetlands and their reporting as much as design efficiency. The data for the table was collated from Evangelisti (1994), Knight, Kadlec & Reed (1992), Meiorin (1989), Silverman (1989) and Swanson (1992).

TSS = Total suspended solids, TP = Total phosphorus, TN = Total nitrogen.

The ability of these natural wetlands to retain nutrients is due to their functions which mimic natural wetland functions. However, as stressed earlier, and by others (Hammer, 1992; Hammer & Bastian, 1989; Hopkins & Argue, 1992; Kusler, 1990; Kusler & Kentula, 1990; Livingston, 1989; Silverman, 1989) there is little uniformity in how these natural wetland functions are incorporated into constructed wetlands. Therefore the remainder of this chapter details the functions natural wetlands that improve water quality then discusses the merits of applying that knowledge to the design of constructed wetlands.

### Functions of Wetlands that Improve Water Quality

Wetlands provide water quality improvement through a number of functions, in particular sediment retention, flood attenuation, nutrient removal or transformation, and toxicant retention. Hydrology is the key factor influencing all of these functions (Kadlec et al., 1993; Mitsch et al., 1993; Wetzel, 1993)

and the specific structure and hydrology of a wetland will determine the water quality improvement functions it will perform (Faulkner & Richardson, 1989; Hammer, 1992; Hammer & Bastian, 1989; Jorgensen, 1989; Olson, 1993). However, while hydrology influences many wetland functions, the reciprocal also occurs. Thus, hydrological conditions affect abiotic elements such as soil structure and nutrient availability, that in turn affect biotic elements, that in turn affect the wetland hydrology (Faulkner & Richardson, 1989; Neiring, 1990; Willard & Hiller, 1990).

### ***Peak Flow Attenuation***

The diversion of stormwater runoff through wetland ecosystems reduces downstream impacts caused by high intensity peak flow. The wetland system functions to reduce the runoff velocity, provide storage and reduce the discharge intensity to receiving environments. A flat basin morphology that contains areas of dense vegetation acts to reduce flow velocity while the wetland storage capacity reduces the volume of flow to receiving environments (Faulkner & Richardson, 1989). Thus, the reduction in downstream impacts resulting from this peak flow attenuation are a function of the wetlands. Discharge from natural wetlands is typically sheet flow (Hammer, 1992; Livingston, 1994). There is little specific research into the peak flow attenuation resulting from wetlands with the function being accepted based on the storage capacity and the flow retarding properties of wetland systems.

### ***Sediment / Toxicant Retention***

The most recognisable function of wetlands water quality improvement is through the trapping of suspended solids. This trapping can be a permanent sink for contaminants in particulate form if continual sedimentation results in the burial of the particulates. If, however, areas of turbulence exist within wetlands, re-suspension of particulate contaminants can result (Tchobanoglous, 1993). Two elements of wetland structure are responsible for this trapping of suspended solids. As mentioned above, flat gradients and dense vegetation are the principle agents responsible for reducing flow velocity (Tchobanoglous, 1993). Deep permanent or semi-permanent pools also reduce flow velocity but are not an essential element in this regard (Evangelisti, 1994).

Amongst contaminants removed by the sediment and toxicant retention function of wetlands are particulate phosphorus and heavy metals. The reduction in total suspended solids (TSS) through wetland function results in a high CRE of phosphorus (Table 2.3). American studies show a fifty per

cent TSS removal efficiency results in a fifty per cent CRE of lead and thirty-five per cent CRE of phosphorus. This relationship is almost linear, with ninety per cent TSS removal efficiency resulting in eighty-five per cent lead and fifty-seven per cent phosphorus CRE in some wetlands (Livingston, 1994). However, these figures assume that phosphorus is in particulate form. The ratio of particulate and dissolved contaminant composition of stormwater runoff determines the relevance of the sediment and toxicant retention function of wetland systems to water quality improvement.

### ***Nutrient Removal and Transformation***

A more subtle, and the least understood, contaminant removal functions of wetlands result from complex soil-water-vegetation interactions such as flocculation, coalescence, adsorption, volatilisation and biological uptake (Tchobanoglous, 1993). The key elements in these interactions are quiescent conditions, the nature of the soil and the vegetation.

Wetland vegetation has two roles in nutrient removal and transformation; direct biological uptake and the establishment of the rhizosphere that facilitates chemical interaction (Mitsch & Gosselink, 1993). The rhizosphere is a narrow aerobic zone surrounding the flooded roots of wetland vegetation and is a major factor in nitrogen transformation. The same sequential process of mineralisation, nitrification and denitrification that occurs at the soil-water interface also occurs in the rhizosphere (Faulkner & Richardson, 1989).

Plant uptake and transformation of nutrients are dependent on nitrate and ammonium concentration in the root zone, the biomass of roots, and the temperature, moisture content and nitrogen concentration in the roots (Jorgensen et al., 1988). Tolerance to poor water quality and extended period of inundation determines the effectiveness of individual wetland plant species (Pullin & Hammer, 1991; Surrency, 1993).

Nutrient storage in macrophyte vegetation is a minor storage pool of short term significance. The recycling of a high percentage of plant biomass through litter decomposition supports that statement (Pate, 1994). Woody species associated with the transition zones of wetlands provide long term nutrient storage but are rarely considered part of the contaminant removal process. Another long term aspect of vegetation is its contribution to the organic content to the soils which in turn enhances the nitrogen removal capability of the wetland (Hammer, 1992).

The major nutrient storage pool in wetland systems is their soils. They either act as a sink for precipitated matter or zones for the chemical interactions that transform nutrients. The chemical interaction occurs at either the soil-water interface, the soil-vegetation-microbe interaction in the rhizosphere or soil-atmosphere interface during dry periods. The type of soil in the wetland determines what chemical interactions occur (Faulkner & Richardson, 1989). Wetland soils are hydric due to the extended periods of saturation and the development of anaerobic conditions that favour hydrophytic vegetation. Substrate classification as either mineral (< 10 - 20% organic matter) or organic (> 12 - 20% organic matter) is relevant to functioning of the wetland. Organic soils have a higher pore space (>80%) than mineral soils (50%) and although higher in water volume they have less hydraulic conductivity due to their poor permeability. This can be critical to wetland vegetation during dry periods (Hammer, 1992; Jorgensen, 1989).

The measurement of the redox potential of hydric soils indicates the level of chemical transformations occurring in the substrate (Faulkner & Richardson, 1989). Wetlands are often the major reducing ecosystem on the landscape. The changes in the redox potential caused by flooding of aerobic soils enables transformations from inorganic inputs to organic outputs, vice versa and a combination of both (Hammer, 1992). Alternating oxidising and reducing conditions enhances nitrogen removal from wetland soils. Aerobic conditions maximise nitrification whilst supplying nitrite for denitrification during anaerobic periods (Faulkner & Richardson, 1989; Jorgensen et al., 1988). This alternating aerobic and anaerobic water column can recharge sorption sites for phosphorus removal. This permits a greater CRE of phosphorus than would happen under constantly anaerobic conditions (Faulkner & Richardson, 1989).

Mineral soils containing high levels of aluminium or iron or calcium favour the removal of phosphorus. The extractable aluminium content of wetland soils directly relate to the long term phosphorus absorption capability of the wetland. However, the capability for nitrogen removal and the toxicant retention of heavy metals and synthetic organic compounds is dependent on the organic content of the soils (Marble, 1992).

An essential element for wetland nutrient removal or transformation is time. Dissolved nitrogen removal requires a residence time of between eight and fourteen days, while dissolved phosphorus

removal requires fifteen to twenty-five days (Crites, 1992; Livingston, 1994) although this will vary with the nature of soil and water.

The review of wetland function above illustrates how complex wetland systems are and how the water purifying function of wetlands results from several components of that complexity. It is insufficient to rely on a single wetland component, for example vegetation, to perform this function. Rather a thorough understanding of the processes enabling the water purifying function is needed in order to allow the structure of constructed wetlands to mimic the contaminant removal functions of natural systems.

## ***Constructed Wetland Design***

### **Overview**

A synthesis of effective constructed wetland design from available literature is not possible due to a lack of uniformity in reporting and evaluation programmes. A summary of constructed wetland design parameters was prepared (Table 2.5) for the synthesis but this illustrated large variation or absence of data such as wetland to catchment ratio, residence time and influent nutrient concentration.

However, a review of American constructed wetlands found that wetlands that successfully met design goals represented a small percentage of projects undertaken. The successful examples exhibited detailed planning and research, construction compliance, thorough reporting mechanisms, evaluation and active management programmes (Kentula et al., 1993). The greater percentage of projects were non-compliant with planning conditions. Many of the reviewed wetlands had an unknown success status due to inadequate monitoring, evaluation and reporting (Kentula et al., 1993). Other studies by Evangelisti (1994), Brown & Reed (1992), and Knight et al. (1992) concur with these findings. Although literature reports a variety of uses for constructed wetlands in urban locations their performance is modelled rather than assessed (Ferlow, 1993; Hopkins & Argue, 1992; Linker, 1989).

The cause of failure of constructed wetlands in the treatment of stormwater is summarised as: a lack of research and project planning, a lack of construction expertise, a lack of reporting and active management programmes, no feed back mechanisms and short cuts in planning or construction (Crites, 1992; Kentula et al., 1993; Hammer, 1992; Livingston, 1989; Silverman, 1989). Although several texts



provide an overview of constructed wetland design (Hammer, 1992; Marble, 1992; Kentula et al., 1993), there is no one recipe for all situations.

This section presents a synthesis of the design process, the design strategy and the design elements to be considered in the development of a successful constructed wetland project.

### Design Process

The design process for a constructed wetland project is not significantly different to any other project. However, the importance of a holistic and coordinated approach to a project that requires manipulation of natural processes cannot be over emphasised. Figure 2.1 outlines the process and emphasises the similarity between the inter-connectiveness of the design process and of the natural elements involved.

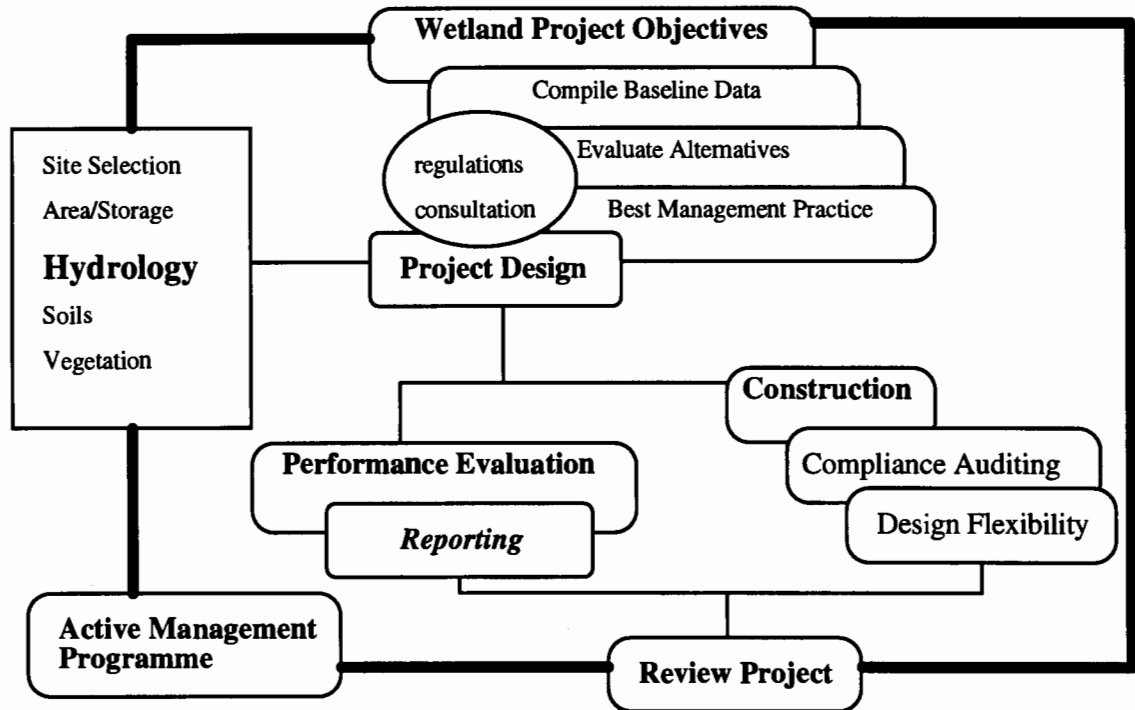


Figure 2.1. Flow chart of constructed wetland design elements demonstrating the interaction of the process and of the natural elements involved.

Table 2.5. Constructed wetland design variation.

Name	site morphology	Catchment/ wetland area [volume]	RT [days]	SW conc. TP TN	Receiving environment	CRE	sampling	Source
Blue Mountains of New South Wales	PT& inflow diffuser, 2 Ponds, 0.6 - 1.2m deep.	26ha/NA [300m <sup>3</sup> ]	1.8	0.154 0.95	creek	load TP - 49 TN - 40	Summer & Spring Storms.	Swanson, 1992.
La Trobe University, Victoria	PT, multi-cell system of billabongs, swamps & lake.	31ha / 0.78ha	33	0.41 3.5	NA	load TP - 85 TN - 78	2 Storms	Graham, 1991.
Des Plaines River wetlands, Illinois	restored riparian wetland.	177 km <sup>2</sup> /182ha (8 wetlands)	NA	NA	Des Plaines River	conc. TP - 55 - 97 TN - NA	NA	Hey et al., 1989.
Old Woman Creek, Ohio USA.	natural marsh.	69 km <sup>2</sup> / 30ha	NA	NA	Lake Erie	conc. TP - 32 - 53 TN - NA	1 year	Mitsch, Reeder & Klarer, 1989.
Fremont, California	lagoon, marsh & sills, with braided channels.	1200ha / 22ha	1 -12	NA	San Francisco Bay	conc. TP - 48 TN - -28	11 storms	Silverman, 1989. Meiorin, 1989.
Orlando, Florida	PT, isolated natural wetlands.	18.9ha / 0.9ha	5	NA	Ground Water	conc. TP - 42 TN - 36	2 years	McArthur, 1989.
Greenwood urban wetland, Florida	PT, 3 ponds & mechanical aeration..	237ha / 5ha	14	NA	closed system	meets Drinking Water std.	ongoing	Palmer & Hunt, 1989.
Lake Munson, Tallahassee, Florida	manmade lake	10600ha / 115ha	NA	1.81 12.1	NA	conc TP - 62 TN - 11	6 storms	Maristany & Bartel, 1989.
Lake Jackson Tallahassee, Florida	3 cells, terraced ponds, filter, marsh.	1010ha / 15ha 50% strms bypass	NA	NA	NA	conc. TP - 90 TN - 76	NA	Esry, Duncan & Cairns, 1989.
Lake Tahoe, California	inflow diffuser; single unit, lined with gravel infill.	1ha / 660m <sup>2</sup>	NA	NA	Lake Tahoe	conc. TP - 47 TN - -3	1.5 years	Reuter, Djohan & Goldman, 1991.

Note. RT = residence time; SW conc. = stormwater inflow concentration; TP = total phosphorus; TN = total nitrogen; CRE = contaminant removal efficiency [load = % of total load retained in wetland, conc. = % reduction in inflow contaminant concentration]; NA = data not available; PT = pretreatment system including gross pollutant traps.

The inter-connectiveness of the design elements within the design process requires an interdisciplinary project team. Such a team must include people from a range of disciplines such as ecology, hydrology, engineering and urban planning. The structure of the team should be egalitarian and not hierarchal to ensure that all the interactions of the design process are understood and complied with (Jorgensen, 1989; Jorgensen & Mitsch, 1989; Mitsch & Jorgensen, 1989; van der Valk, & Jolly, 1993; Walsh, 1994; Wetzel, 1993; Wilcox, 1988).

## **Design Strategy**

### ***Objectives***

The prime objective of a constructed wetland for stormwater treatment must be effective contaminant removal. Sediment and toxicant retention, nutrient removal or transformation, or flood attenuation are the focus for urban runoff treatment wetlands. However, constructed wetlands have the potential to be multi-purpose sites and design can incorporate multiple objectives. Other wetland functions such as habitat creation, landscape enhancement or recreation are secondary objectives and must not compromise the primary objective (Hammer, 1992; Marble, 1992; Mitsch, 1993).

Statutory regulations concerning the environmental quality of receiving environments often determine the design objective (Fields, 1993). These regulations will be project specific and are likely to vary between national, state or local agencies. The standard method of stating the contaminant removal objective is either as a desirable concentration level of the effluent or a reduction in the loading to the receiving environment (Australian Environment Council, 1988). Modelling of contaminant loads to the wetland will assess the potential for a constructed wetland to achieve that objective.

### **Design Principles**

Once established, the major objective dictates the individual elements of the wetland. In dealing with the design of these elements it is necessary to consider the ecological principles of the ecosystem being engineered. The major ecological principles considered are:

- the wetland hydroperiod is the forcing function determining ecosystem structure and function. This forcing function includes precipitation, nutrient content of flow, inflows of

water, evapotranspiration and temperature (Jorgensen et al., 1988). Therefore wetlands will adjust and self-design to the prevalent conditions.

- the structure and function of the wetland determine the recycling of elements in ecosystems. The equilibrium of the system is determined by the relationship between biological function and chemical composition. Therefore, alterations to the forcing functions will cause significant changes to equilibrium of the wetland (Jorgensen & Mitsch, 1989).
- processes in wetland have characteristic time scales that may vary over several orders of magnitude. The components of the wetland also have characteristic space scales (Kentula et al., 1993). Thus to achieve the desirable equilibrium, spatial and temporal scales must be coordinated.
- the ability of a wetland to adapt to a variety of conditions is determined by the buffering capacity afforded by chemical and biological diversity of the wetland (Hammer, 1992; Mitsch, 1993). That is, the more complex the wetland design, the more versatile and robust the wetland. Mono-feature wetlands will be susceptible to any alteration in forcing function.
- wetlands are ecotones between terrestrial and aquatic ecosystems that are most vulnerable at their boundary. Buffer zones enable undesirable changes imposed from neighbouring systems to be absorbed without impacting on the wetland (Mitsch, 1993).
- everything is linked to everything else, within the wetland and between the wetland and its surroundings. Therefore a change to one component in design will affect change in another and so on (Jorgensen & Mitsch, 1989; Tchobanoglous, 1993).
- wetlands have pulsing patterns and the components of the system must be able to tolerate extremes (Loucks, 1990; Jorgensen & Mitsch, 1989; Tchobanoglous, 1993). Design must allow for the inherent variability in the hydrological cycle.

A common failing of constructed systems is the tendency to over engineer and manage the wetland in an effort to reduce area requirements. This does not allow for the necessary temporal and spatial

requirements of removal functions. If the wetland system is to be viable and sustainable it must be allowed to self-organise (Odum, 1989; Smith et al., 1993).

### **Project Design Elements**

There is a logical sequence of data collection and evaluation for constructed wetland design. The first step in the sequence being site selection and evaluation.

#### ***Site Selection and Evaluation***

A major constraint in the location of the constructed wetland site is the source of stormwater runoff since relocating that runoff by channelling or pumping represents an undesirable cost alternative (Hammer, 1992). Other constraints include: land ownership and land use, and existing topographical, geological, hydrological or biological conditions. Besides collating data on potential sites, adjacent lands need to be assessed for potential impacts from the constructed wetlands. Two elements are of particular importance. The first is a detailed water quality analysis of receiving environments and expected discharge quality to evaluate and monitor potential impacts. The second is part of ICM. Consultation with existing and adjacent landowners with setting out the project goals, proposed development and potential impacts will reduce community resistance (Hammer, 1992).

A major element of site evaluation is the assessment of existing conditions with design elements of CRE objectives. The elements of major consideration for constructed wetlands are its morphology, hydrology, substrate, and vegetation.

#### ***Contaminant Loadings***

Studies show optimum CRE at low loading concentrations for wastewater wetlands (Mitsch & Gosselink, 1993). To achieve a 50% CRE of nitrogen, loading should not exceed 25 g N/m<sup>2</sup>/yr, while for 65-90% CRE of phosphorus the loading rate should be less than 5 g P/m<sup>2</sup>/yr. The CRE of phosphorus decreases significantly with increased loadings. Loadings greater than 10-15 g P/m<sup>2</sup>/yr will result in CRE of between 30-40% or less and an accumulative effect that could result in phosphorus export within five years (Faulkner & Richardson, 1989). Studies on seventeen wastewater wetlands also displayed a strong correlation with loading rate of ammonia and the required treatment area (Hammer & Knight, 1992):

$$A = 1.8312(N \times Q) / 1160.6$$

where A = treatment area in hectares,

N= influent  $\text{NH}_3$  concentration in mg/L ,

Q = average daily flow in  $\text{m}^3/\text{day}$ .

It is not known whether this wastewater data is directly transferable to stormwater constructed wetlands. Specific research into the effect of loadings resulting from stormwater inputs is necessary for effective constructed wetland design (Hammer, 1992; Livingston, 1989).

### ***Wetland Hydrology***

Hydrology or precisely the hydroperiod of the wetland is the dominant forcing function for wetland ecosystems. The dominant processes effecting wetland hydrology include: atmospheric circulation, precipitation, evapotranspiration, surface flows and groundwater flows. There is a contradiction in literature on the relevance of groundwater. While considering groundwater flows unimportant in wetland processes the literature acknowledges a lack of data on dominant processes that control water level fluctuations, particularly shallow surface and near surface water movement (Duever, 1988). Modelling of the hydrological functions is of use in understanding important parameters but it is of limited use in management problems unless the model is bolstered with specific site detail (Duever, 1988). Water exchanges with the atmosphere add to the complexity of constructed wetland hydrology. Rainfall can dilute the resident treatment water and increase the outflow velocity. This can present a higher CRE than is actually the case. Conversely, evapotranspiration can increase the concentration of the resident water and appear to lower CRE (Kadlec, 1989).

While it is inadvisable to ignore the effects of atmospheric augmentation, the water residence time as a factor of storage volume and flow pattern is the major design element for constructed wetland CRE.

### ***Residence Time of the Stormwater in the Wetland.***

The residence time of inflow water directly influences sediment retention and nutrient removal or transformation functions of wetland systems. Studies in American constructed wetlands showed a direct relationship with TSS reduction and particulate contaminants existed with 80-85% reduction in TSS after three days having a potential CRE of 60% of heavy metals and nutrients (Evangelisti, 1994; Livingston, 1994). From those studies a minimum residence time of three days was as necessary for effective TSS removal. However effective CRE for nutrients in dissolved form requires a significantly

longer residence period. In wastewater wetlands it was found that significant dissolved Nitrogen removal required eight to fourteen days, while phosphorus in the dissolved form required fifteen to twenty-five days (Crites, 1992).

The residence time of a waterbody is accepted in literature as a direct relationship between input volume and the storage capacity of the wetland and is generally expressed thus:

$$\text{Residence Time (days)} = \frac{\text{Storage Volume of wetland}}{\text{Input Volume per day}}$$

This determination of residence time assumes that there is little or no hydraulic gradient within the wetland and that the flow pattern closely approximates plug flow. These aspects are discussed in the section on Basin Morphology.

### ***Storage Volume***

The rule-of-thumb accepted for treatment volume of wetlands or wet detention basins is 90% of runoff producing storms on an annual basis. The standard formula for calculating the required treatment volume is:

$$\text{Treatment Volume} = \text{Coefficient of volumetric runoff} \times \text{Runoff from selected rainfall event} \times \text{Catchment area.}$$

Treatment volume is distinct from storage volume where permanent water bodies are present. Storage volume is the general term used here. It is important that the above calculation is applied to the whole of the runoff generating catchment area. In addition, all wetland water budget elements need consideration to avoid under-estimating inputs and these can be addressed using the generally accepted water budget formula (Evanglisti, 1994; Livingston, 1994):

$$\text{Direct Precipitation} + \text{surface inflows} + \text{subsurface inflows} = \text{surface outflows} + \text{subsurface outflows} + \text{evapotranspiration.}$$

The selection of the rainfall event is the critical element in determining storage volume. Cross referencing of the calculated volume with residence time requirements for CRE objectives is essential. Computer modelling of storm intensity and frequency generation of runoff in urban environments is an effective means of evaluating residence time and storage requirements of constructed wetlands (Straskraba et al., 1988). The following examples of constructed wetland projects that employed extended or continuous monitoring programmes exhibited a variation in CRE related to their

hydrological cycle. These studies highlighted design shortfalls in inadequate temporal and spatial allowances for runoff to enable the constructed wetlands to function effectively.

Examples of America constructed wetland systems that reported the correlation between intense storm events and poor CRE are the Lake Tahoe and Fremont projects in California and Lake Jackson in Florida. The Lake Tahoe system reported CRE of -28% for reactive phosphorus but +47% for total phosphorus (Reuter et al., 1991). The Fremont system reported similar variations in CRE for phosphorus while the system had a CRE of -28% for nitrogen (Meiorin, 1989). Short circuiting or bypassing of the system during intense storm events was the major cause of the variation in CRE. The Lake Jackson system evaluation also attributed the CRE variation to intense storm events with 50% of storms bypassing the wetland (Esry, Duncan & Cairns, 1989). Australian constructed wetland projects are poorly represented in literature. Projects in the Blue Mountains (Swanson, 1992) and La Trobe in Victoria (Graham, 1991) have a limited evaluation period but support the findings of the American literature. The monitoring programme for the Bartram Road constructed wetland provides detailed performance evaluation that correlates poor CRE with peak flow (Dean et al., 1994).

Constructed wetlands with permanent water, either as ground water infiltration or due to proposed artificial lining, have a modified storage calculation. The treatment storage is the volume above the permanent water. Systems with permanent water have removal efficiency characteristics in proportion to the ratio between the runoff generated by the mean storm event and the volume of permanent water. A ratio of between 4 to 6 will produce maximum removal rates (Evanglisti, 1994). These rates relate primarily to the removal of particulate matter.

### ***Wetland Morphology***

Constructed wetland morphology is the physical expression of residence time and treatment volume requirements. There are several generalisations that determine constructed wetland basin morphology. The first rule-of-thumb is that surface area should be 2-5% of the catchment area (Livingston, 1989). Another rule-of-thumb is that the basin aspect ratio be a minimum of 2:1. The aspect [length to width ratio] is critical to ensure a long flow path (Fennessy & Mitsch, 1989). The optimum basin cell aspect ratio is between 3 and 4 (Evanglisti, 1994; Hammer, 1992). Larger ratios reduce short circuiting potential but are not cost effective (Crites, 1992).



Both sediment retention and nutrient removal or transformation depend on quiescent conditions (Evanglisti, 1994). Flat, level and densely vegetated areas that induce low velocity sheet flow produce the required quiescent conditions. The desirable peak flow velocity through wetlands should not exceed 0.45m/sec (Evanglisti, 1994). Establishing a minimal flow rate through the constructed wetland system reduces the potential for sediment resuspension during peak flow periods.

The desirable cross-section of wetland basin morphology is a flat base with gentle banks. This cross-section permits an increase in surface area during peak flow thus allowing the same water-soil-vegetation interactions as median flows (Fennessy & Mitsch, 1989). Steep sided embankments have the disadvantage of providing possible contaminant inputs through bank erosion and the introduction of safety hazards in wetlands with public access.

The design purpose of constructed wetland basin morphology is to produce a shallow (0.1 - 0.5m), slow moving plug flow (Crites, 1992). The explanation of plug flow is a flow pattern where inflow totally displaces the resident water and travels through the wetland as a uniform body of water. The production of a true plug under natural conditions is unlikely. Residence time calculations need to allow for a degree of lateral and longitudinal mixing that occurs in natural systems (Kadlec et al., 1993). The advantage of a shallow, slow moving flow pattern is the maintenance of aerobic conditions within the water body. This reduces the nuisance factors of odour and the mineralisation of phosphorus associated with anaerobic processes. Particular elements to avoid in basin morphology design are dead zones, where water will stagnate becoming anoxic, and the channelisation of water that will reduce design residence time.

Discharge from the constructed wetland influences the CRE of the system. The ideal for sediment and contaminant trapping is a closed system that has no discharge. This considerably increases the storage and hence the area requirements of the wetland that may not be practical or indeed desirable. Outlets should be constrictive, prohibiting rapid discharge that will effect the wetland functioning and impact on receiving environments.

The above guidelines project a simple system primarily concerned with contaminant removal through sedimentation. Constructed wetland treatment of urban stormwater often has CRE objectives more

complex than that discussed above. To achieve these complex objectives the constructed wetland structure must become more complex.

For example, nitrogen removal or transformation is via three primary processes, ammonification-nitrification-denitrification, that require a combination of aerobic and anaerobic environments. Studies on seventeen wastewater wetlands showed that if 10-20% of the wetland area has a minimum depth of 1.5m and arranged intermittently and perpendicular to the flow path the necessary conditions for nitrogen removal were met. Incorporating deeper sections also reduced the requirement for large aspect ratios with ratios of 2:1 the most cost effective. In addition the deeper sections reduced short-circuiting by redistributing water to sheet flow (Hammer & Knight, 1992).

This type of complex structure is difficult to achieve in a single unit system. However, multi-cell constructed wetlands incorporate varying wetland CRE functions in different cell structures. The first cell or forebay to the wetland shaped as an inverted funnel would reduce the velocity of inflow and distribute the water evenly to densely vegetated basins. This cell also functions as a storage and sedimentation unit. Separation of this function from the rest of the wetland will allow sediment removal and minimise the impact of that operation on the remainder of the wetland. Subsequent densely vegetated, flat and level cells downstream of the forebay can be incorporated to perform nutrient removal and transformation functions. These cells occupy the greater percentage of the wetland surface area. The last cell would have the primarily function of storage. This would also encourage further precipitation of contaminants and permit controlled discharge. It is essential that the design of a complex constructed wetland incorporates sheet flow between cells. Channelisation of flow produced by ditches or culverts will reduce the effectiveness of the cell design. Examples of successful multi-cell constructed wetlands exist at La Trobe (Graham, 1991) and Fremont California (Meiorin, 1989).

Simulation modelling of nutrient retention is a valuable tool for the design of simple and complex basin morphology. Studies conducted on two wetlands (marshes) in Denmark use forcing function such as precipitation, nutrient content of flow, inflows of water, evapotranspiration and temperature (Jorgensen et al., 1988). Modelling of nutrient loads enables a determination of treatment area that will achieve the objective CRE.

### ***Substrates***

The type of substrate in the wetland effects the range of interaction possible. The soils “*provide support for wetland plants, are the medium for many chemical transformations, and are the principle reservoir for minerals and nutrients needed by plants.*” (Hammer, 1992). Substrates are the major nutrient storage pool within wetland system. Studies have shown that up 90% of Total Nitrogen and 70% of Total phosphorus within wetland storage pools are contained in the substrate (Faulkner & Richardson, 1989). In constructed wetland sites that do not have existing wetland substrates such as organic rich soil amelioration can significantly increase the nutrient retention capacity of the new system.

Nitrogen removal, toxicant retention of heavy metals and synthetic organic compounds are associated with organic soils (Marble, 1992). Phosphorus removal is dependent on maintaining water contact with soils high in calcium, or oxalate-extractable iron and aluminium (Faulkner & Richardson, 1989; Marble, 1992). Maximum soil capacity for phosphorus retention varies widely making substrate selection critical for long term phosphorus CRE (Faulkner & Richardson, 1989).

Several studies on phosphorus adsorption capacity of various soils have been conducted and it is of note the significant difference between the local natural sands and ameliorated soils (Table 2.6). Studies by Sampson (1994) on the use of bauxite residue to remove phosphorus from wastewater found that a mix of red sand and 5% gypsum had a maximum adsorption capacity of 203µg/g which was a 30% increase on the same property in red mud. Although red mud has a higher PRI than red sand, the fine particles tend to clog and become impermeable. Red sand and red mud are the trade names given to bauxite refining residue. Red sand is the fraction of the residue greater than 150µm (Sampson, 1994). Studies by Mann and Bavor (1993) compared gravel substrates to industrial waste substrate and found that fly ash (260µg P/g) and slag (160-420µg P/g ) had greater phosphorus adsorption than the gravel (26-48µg P/g).

Regardless of whether the constructed wetland substrate is amended or left natural, the adsorption capacity should be determined in order to predict the long term phosphorus retention capacity of the wetland.

Table 2.6. The relative permeability of water and PRI of various substrates available in Perth.

Substrate	Permeability (m's per day)	PRI
Bassendean Sand	30+	0-0.5
Karrakatta Sand	10+	3-4
Crushed Limestone	2-5	80-100+
Red Sand	0.5-5	80-100+
Red Mud	0.1-1	200+

Note. PRI = phosphorus retention index. Limestone PRI varies with calcium content of source material. Source of data Kayalp et al., 1988

### **Vegetation**

The functional role of constructed wetland vegetation is inter-related to other wetland elements: soil, hydro-period, and contaminant loadings and contributes to the functioning of these elements (Meney, 1994). Densely vegetated areas increase friction to the flow path, reducing velocity and enabling entrapment of particulate matter (Guntenspergen et al., 1989).

Criteria for wetland vegetation are project specific and dependent on the properties of the runoff and CRE objectives (Guntenspergen et al., 1989). Heinsohn and Cunningham's work (cited in Meney, 1994) in South African wetlands has shown that dominant species may not be in optimum conditions, but merely out compete other species. Research on Western Australian wetland vegetation has shown it to be typically adapted to poor nutrient conditions. Invasion of, or the deliberate planting of European or South African high nutrient requiring species can displace endemic species not only in the constructed system but neighbouring natural systems (Pate, 1994). This potential impact is avoided with particular care in vegetation design.

The emergent species selected should be robust, have a high biomass, obtain optimum growth in 2-3 years in hyper-eutrophic conditions and be locally available (Chambers & McComb, 1992; Meney, 1994). Research into optimum conditions of nine local species gave best results for plants established in sandy substrates with shallow water (less than 300mm) and some water movement. Plant growth positively correlated to oxygen levels in the substrate (Chambers & McComb, 1992). Studies supporting these findings showed that plants subjected to extended periods of deep water had lower nutrient uptake and reduced nutrient storage (Rea & Gnaf, 1992).

Harvesting of constructed wetland vegetation as a means of nutrient removal is not recommended. The theory of harvesting for permanent removal of nutrients may be counterproductive as seasonal growth conflicts with wet season (Lowe, et al., 1989; Pate, 1994). Harvesting is only considered to maintain hydraulic capacity, promote active growth or to avoid mosquito breeding (Crites, 1992).

The area, density, diversity and homogeneity of vegetation influence the flow pattern of wetlands. Homogeneous vegetation areas produce predominantly plug flow regimes with some longitudinal dispersion. Conversely, inhomogeneous areas produced inhomogeneous flow with partly stagnant zones (Netter, 1992). The frictional force of reed beds reduce flow velocity by 1/3 to 1/2 of shore line velocity. This effect is particularly relevant where water depth exceeds 300mm and the bottom roughness is negated. The reduction in flow velocity to less than 0.1cm/sec enables fine particle settling within reed beds (Hosokawa & Furukawa, 1992). A low vegetation-water interspersed characteristic (reduced expanse of open water) matched with a high percentage area of vegetation to open water ratio will maximise the entrapment function of emergent vegetation (Marble, 1992).

A diversity of selected vegetation will increase the complexity of the constructed wetland that in turn will increase the ability of the system to adapt to adverse conditions. American experience shows that constructed wetlands use less than 1% of the available taxa with emergent macrophytes the dominant form (Hammer, 1992). However, aquatic floating or submergent species and terrestrial woody plant species are important to wetland structure. Floating species have high growth rates, large standing crops and ability to strip nutrients directly from the water column. Their roots provide sites for filtration and adsorption of suspended solids as well as growth of microbial communities that sequester nutrients from the water column. The role of submergents would appear limited in CRE as these species are generally intolerant of eutrophic conditions, particularly water that is highly coloured or has a high level of suspended solids. However, their role should be considered in conjunction with emergents and complexity of habitat creation (Guntenspergen et al., 1989). Woody plants provide long term nutrient storage and a buffer to possible adverse inputs from adjacent land use (Meney, 1994).

A major consideration in constructed wetland vegetation selection is the creation of a viable persistence system. Such a system will be dynamic and will alter in structure as it adapts to the prevalent conditions. A distinctive but fluctuating hydrological regime will characterise the constructed wetland.

The changes that occur will not be directional and generally not predictable. The fluctuating water levels, chance and catastrophe are constantly interacting and will cause trepidation for design teams (Neiring, 1990). However, the system design must aim at self-perpetuating the vegetation assemblage.

## ***Constructed Wetland Management***

Assessment and active management programmes are an integral part of the design process (Kentula et al., 1993). The discussion so far on design elements places an emphasis on allowing the systems to be self-organising, however this does not imply a build and forget philosophy. It is essential that the required resources for the project management be allocated and costed at the initial design stage. Given the high labour component, the technical nature of analysis and the ongoing requirement of management, these costs will constitute a significant proportion of the project budget (Erwin, 1990). This is not a disadvantage of constructed wetlands, rather an essential part of stormwater management, regardless of the treatment system employed.

## **Performance Evaluation & Review**

Unfortunately, performance evaluation and review of a constructed wetland project is often neglected and is the probable cause of reported variations in performance and design elements (Brown & Reed, 1992; Knight et al., 1992). A disadvantage of constructed wetland treatment is the lack of knowledge on effective performance life of a wetland. Only an effective monitoring and assessment programme can determine the long term effectiveness of constructed wetlands (Bartel & Maristany, 1989; Maristany & Bartel, 1989; Wilcox, 1988).

Kentula et al. (1993) identifies three levels of assessment that support effective project performance evaluation and review: compliance auditing ('as constructed'), CRE monitoring and comprehensive assessment. Each of these assessments is detailed as individual entities in the following sections. This treatment of the assessments is for clarity and it must be emphasised that they are inter-connected and complimentary.

## ***Compliance Auditing***

Given that expert supervision is employed in constructed wetland projects, this element should require minimal resources to up-date construction plans to 'as constructed'. However, this stage is important,

not only as a compliance requirement but to ensure that variations that inevitably occur during construction projects do not adversely effect the design objective criteria.

The purpose of 'as constructed' assessment is to compare the finished product with design objectives and ensure the project is in compliance with approval conditions (Erwin, 1990; Hammer, 1992; Kentula et al., 1993). The second objective of assessment at this stage is to provide baseline data for future assessment. To satisfy this criterion the compliance or 'as constructed' assessment should include the following data collection (Kentula et al., 1993);

- area mapping of basins and establishment of basin morphometry transects,
- vegetation mapping and establishing transects for future assessment,
- substrate assessment, including a contaminant suite analysis and
- photographic stations for visual recording of the wetland development.

### ***CRE Objective Monitoring & Reporting***

CRE objective monitoring is part of compliance conditions, however to emphasise the distinct requirements of performance evaluation it is considered separately in this report. The design of CRE objective monitoring programmes includes the following minimum elements (Kentula et al. 1993):

- continuous inflow and outflow monitoring.
- intense contaminant analysis of inflow and outflow, particularly during the wetland establishment period and
- a minimum of annual recording of data listed in 'as constructed' assessment.

CRE objective monitoring has the potential to represent a high proportion of operating budgets. This cost can be offset by including auto-samplers, data loggers and housing structures into the capital costs of the budget. The labour component of sampling can then be rationalised by utilising the refrigeration and bulking facilities of auto-samplers such as the Isco 6700 series. This can reduce the need to collect bulked samples to weekly intervals.

Other factors to design into an effective monitoring programme are the requirement for data validity and reliability though quality control of sampling and analysis. The reporting mode and interval will directly influence the design of active management programmes (Reinelt et al., 1992). Much of the literature suggests that the performance monitoring need only be conducted during the early years of the wetland establishment and until the system has reached an "equilibrium". This approach appears to be a rationalisation for economic reasons. It must again be emphasised that stormwater is a significant pollution source and while that source exists, treatment of it must be continually monitored.

### ***Comprehensive Assessment***

A well designed and constructed wetland will continue to evolve, reacting to the specific conditions that determine the function and structure of wetlands (Odum, 1989b). In most instances this dynamic nature of wetlands will result in gradual change to the wetland structure (Mitsch & Gosselink, 1993). An example of possible unplanned events that could adversely affect CRE of constructed wetlands is the contribution of large bird colonies to nutrient inputs of wetlands (Baxter & Fairweather, 1994). This type of change to wetland structure would not be detected in routine assessment.

Comprehensive assessment is not a stand alone assessment and can be completed in conjunction with data from compliance auditing and routine monitoring. The requirement for a comprehensive assessment of constructed wetlands is at three to five year intervals (Kentula et al., 1993). This assessment should include all the routine assessment detail plus a flora and fauna inventory and a wetland assessment based on systems employed for natural wetland evaluation. Suitable guidelines for wetland evaluation on the Swan Coastal Plain are in the EPA Bulletin No. 374 (1990). Guidelines from No. 374 are designed to assess conservation value of natural wetlands and as such present an opportunity to evaluate secondary objectives of wetland projects such as community acceptance.

The comprehensive assessment of constructed wetland projects should also include a definitive classification of the wetland. The classification system for wetlands proposed by Semeniuk (1987) is based on landform and water permanence, and has shown to have a high co-relation for the Swan Coastal Plain. The adoption of the Semeniuk classification in reporting will provide a common data base necessary for review and comparison within and between various projects.



### Active Management Requirements

In conjunction with design objectives and performance evaluation it is essential that operating procedures are designed to allow corrective action if the need arises. For example, management issues such as; water quality management, structure integrity or weed and pest control require operating procedures that cover goals, problem identification and causal factors, appropriate strategies, lead time and evaluation of control measures (Tchobanoglous, 1993).

Mosquito control is likely to be an operational priority for constructed wetlands located close to residential areas. As mosquitos are common inhabitants of natural wetlands it is to be expected that they will invade constructed wetlands. Their ideal habitat consists of standing nutrient rich water with vegetation cover and in particular anaerobic, bacteria-laden water bodies (Olson, 1993). Suggested management actions to control mosquito populations such as vegetation slashing, introducing *Gambusia* spp., or the use of insecticides, are counter-productive to the performance objectives of constructed wetlands (Crites, 1992; Hammer, 1992). It is therefore essential that appropriate design criteria be adopted to reduce mosquito habitat. Standard operating procedures that regularly check for blockages within the system and permit debris removal will reduce stagnant zones thus minimising mosquito habitat.

Over management or excessive manipulation of wetland function is a potential danger to the development and effective performance of constructed wetlands (Guntenspergen, Keough. & Allen, 1993; Mitsch, 1993). However, appropriate management strategies will improve the operation and performance of constructed wetlands (Tchobanoglous, 1993).

### Capital Costs

It would be misleading to quote an average \$/hectare cost as there are as many variables in the cost structure between regions as there are in design variables between wetlands. For example, constructed wetlands projects to treat mine drainage in Tennessee ranged from \$3.58/m<sup>2</sup> to \$32.03/m<sup>2</sup> (Wieder et al., 1989). Rather it is appropriate to reiterate that all the elements contained within the design process need to be realistically costed (Mitsch & Gosselink, 1993). It is highly desirable that funding be matched to optimum design costs rather than the project fitted to available funds. The latter is likely to compromise performance that will result in the failure to achieve CRE objectives. This in turn will squander scarce

funding and alienate the potential for constructed wetland treatment of stormwater runoff in future projects.

### ***Bayswater and Jandakot Constructed Wetlands***

The use of constructed wetlands to treat urban stormwater runoff in Perth is in its infancy and demonstrates a significant variation in design strategies to achieve relatively similar CRE objective criteria. The following critique on the design of three constructed wetland projects in the Perth region uses the criteria established in the previous section.

#### ***Russell Street Biological Filter***

The Russell Street constructed wetland project is unique in that it forms part of a strategy to redress an existing stormwater runoff problem. The project is one of two pre-existing compensating basins on the Bayswater Main Drain that have converted to constructed wetlands (Figure 4.4). The location of the Russell Road constructed wetland is next to Russell Street opposite the Galleria Shopping centre and about 500m east of Walter Road in the district of Morley. Federal grants under the Western Australian Sewerage and Water Quality Infrastructure Programme funded the project (W G Martinick & Associates Pty Ltd., 1994). Construction work and associated vegetation planting by volunteer groups was completed late 1994. Planting of buffer vegetation is scheduled for 1995/96.

#### ***Performance Evaluation***

To date there has been no thorough performance evaluation of the Russell Street constructed wetland. A preliminary evaluation was performed as part of this study and is presented in chapter 4. It indicated a negative Total Phosphorus CRE for the short study period in August 1995. A monitoring and assessment programme commenced during the winter of 1994 (W G Martinick & Associates Pty Ltd., 1994) and the results will be available by the end of 1995. Monitoring on the Bayswater Main Drain during twenty-one storm events in 1992 provided the runoff assessment for the project design (W G Martinick & Associates Pty Ltd, 1994).

#### ***Design Objectives***

The Russell Street project had three design objectives: a target phosphorus removal of 50%, a seven day retention time of input waters during the winter months, and the secondary objective of landscape

enhancement (W G Martinick & Associates Pty Ltd., 1994). The objectives of the Bayswater Integrated Catchment Management Committee were considered in the site location, function and landscape enhancement of the Russell Street constructed wetland project (Klemm & Switzer, 1994).

The basin design to achieve the project objectives had a treatment volume of 250m<sup>3</sup> per hectare of catchment (approximately 10000m<sup>3</sup>). The planted macrophyte coverage was to be 50% of the surface area. A variation in basin depth from about 1m to between 2 - 3m was designed to provide nutrient stripping and sedimentation functions.

### ***Design Critique***

An 'as constructed' assessment was not conducted on the Russell Street project. Preliminary field work conducted as part of this report indicates that there were considerable changes between design and the completed project (WAWA, 1993). Figure 4.4 illustrates the physical parameters of the Russell Street project.

Surface Area & Basin Morphology. The surface area is approximately 1% of the catchment area. The depth of water is more than 1m, with the deepest portion over 2m as a narrow trough on the eastern bank near the outflow structure. The depth of water will prohibit the establishment of dense emergent macrophyte banks. The establishment of submergent macrophytes is unlikely due to the stress placed upon them by the turbid stormwater inputs and depth at maximum storage (>2m). Stabilisation of the basin banks could be difficult to achieve. The slopes at 1:2.5 have shown signs of destabilising during the planting operations. Banks of this grade also present a safety hazard in that the water depth increases rapidly.

The construction of an island increases the flow path and provides an area of vegetation for nutrient uptake during periods of low flow. However, flooding of the island occurs during periods of moderate or high flow. This negates the beneficial effects of the island and allows short-circuiting of the inflow water.

Storage volume. Whilst the total storage capacity meets design criteria, treatment storage is considerably less when allowing for permanent groundwater. This reduced storage capacity was observed in tracer dye flow studies conducted during a moderate storm event in July 1995 (chapter 3).

The residence time of the constructed wetland system determined during those flow studies was approximately twenty-four hours. Assuming the summer groundwater levels given in design criteria, approximately 5000m<sup>3</sup> is available as treatment volume. Flow data from runoff monitoring of twenty-one storm events in 1992 (cited in W G Martinick & Associates Pty Ltd., 1994), converted to a histogram of residence time occurrences (Figure 2.2), shows that only seven of those storm events would have a theoretical residence time greater than three days. This data supports the findings of the flow trials and suggests that the wetland is under-designed to achieve consistent CRE of nutrients in any form.

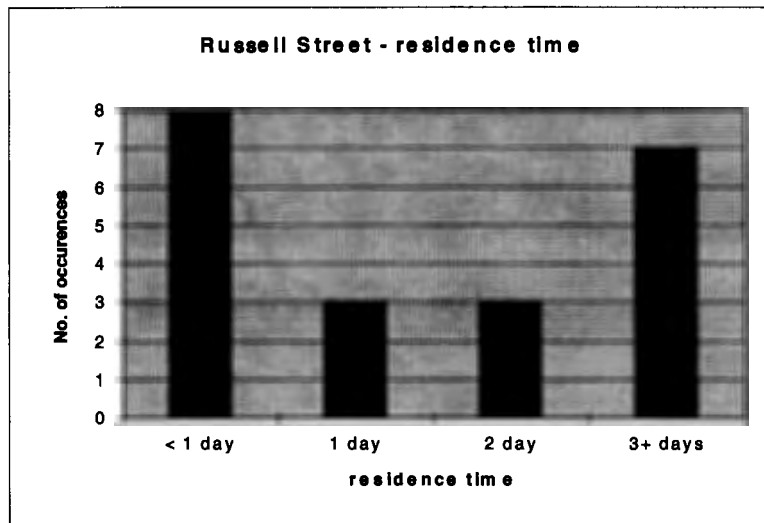


Figure 2.2. Histogram of theoretical residence time occurrences for twenty-one storms monitored during 1992 in the Russell Street catchment.

**Vegetation.** Due to the basin design, only a small fringing area is available for emergent macrophytes (Figure 4.3). The vegetated area constitutes about 5% of the constructed wetland surface area. Given the present basin morphology it would not be possible to meet the 50% coverage stated in the design objectives.

**Stormwater Inputs.** The Russell Street constructed wetland has eight input points. The branch of the Bayswater Main Drain is the major contributor while five of the inputs are from adjacent commercial properties and are relatively insignificant but two inputs on the north side of the basin are significant. They drain large carpark or road catchments and create two problems for the effective operation of the constructed wetland. First, the volume and velocity of inflow from these inlets significantly alter the flow pattern during moderate to intense rainfall events. This causes short-circuiting of the flow path and

results in shorter residence times. The second impact of these inlets is that the velocity of the inflow disturbs the sediments within the immediate area of the inlets. This may cause the re-suspension of trapped nutrients and negate, to some degree, the particulate removal achieved during periods of quieter flow.

Operational Guidelines. Observations of drain vegetation slashing operations showed the operation resulted in considerable quantities of slashed material entering the constructed wetland. This produces an unnecessary nutrient load to the system. The artificial bank stabilisation at the outlet structure to the constructed wetland and the adjacent drain is eroding and will undermine the structure and provide sediment input to the downstream drain.

Monitoring and Assessment. The assessment programme being undertaken by W G Martinick & Associates Pty Ltd will provide valuable data on the functioning of the constructed wetland. However, evaluation of CRE would require considerable extrapolation from a limited number of samples. This would most likely result in either under or over estimation of CRE.

### ***Management Action***

The CRE of Russell Street is not fully known but it is unlikely to be effective other than for sediment trapping during low to moderate rainfall events. Improved effectiveness could be achieved by reviewing and amending the following;

- all inlet points should be diverted to the one area. This would require mainline relocation and the installation of either a mechanical diffuser or construction of a forebay.
- review the storage requirements for effective contaminant removal from stormwater runoff. The minimum requirement is to accommodate 90% of annual peak flows whereas the optimum treatment storage will accommodate all known peak flows. Given that the CRE objective of this project was a 50% reduction in phosphorus a minimum residence time for the treatment storage is fifteen days.
- incorporate more of the available land into the constructed wetland. At present, less than 60% is utilised. This would involve incorporating the adjacent contributory drains not presently treated within the constructed wetland. The narrow entry and exit drains provide the potential to significantly increase the treatment area and should be incorporated into the constructed wetland

design. The treatment of these drains as creek lines rather than open drains will not only improve CRE but provide an attractive urban landscape (Bowmer & Bales, 1992; Pen, 1994).

- review the depth of the existing basin. Elevating the base level to or just above the water table will provide suitable conditions for the establishment of dense reed beds. Such reed beds will increase the water - soil - plant interactions and significantly increase the CRE of the wetland. The shallower profile for the basin will enable assimilation of inflow volumes via an increase in surface area rather than an increase in depth that also increases the discharge rate.
- a commitment to treating stormwater involves a comprehensive monitoring programme. Semi-permanent stations need to be established at the inlet and outlet points. The role of such stations is to provide continuous flow data and water quality monitoring. The programme currently undertaken by W G Martinick & Associates Pty Ltd would provide the functional assessment requirement of constructed wetland projects.
- review operating guidelines on vegetation slashing of drains with the aim to reducing clippings transported downstream.

### **Hird Road Detention Basin & Wetland**

The Hird Road buffer lakes consist of a constructed detention basin connected to a natural wetland located on the east side of Hammond Road and north of Hird Road in the Jandakot district (Figure 4.9). The purpose of the system is to treat stormwater from a catchment of approximately 1.2 km<sup>2</sup> (Deane et al., 1994). Urban development will eventually cover 40% of the catchment. The requirement to treat the stormwater runoff is a condition of approval for the South Jandakot Drainage Scheme (G B Hill & Partners, 1990 & 1991).

### ***Performance Evaluation***

The Hird Road system has been operational since August 1993. The water quality monitoring has not been as comprehensive as that for Bartram Road, however from the data presented in Table 2.7, the wetland system appears to be a source of nutrients rather than a sink.

The Hird Road constructed wetland system CRE criterion is assumed to be that of the South Jandakot Drainage Scheme. This criterion aims to reduce phosphorus inputs to the Beeliar Wetland chain by

30% (G B Hill & Partners, 1990 & 1991). On the basis of 1994 data this target is clearly not being met (Table 2.7). The study on nutrient retention at Hird (chapter 4) during August 1995 also indicates that the design objectives are not being met.

Table 2.7. Hird Road Wetland Drainage System Monitoring Data Summary for the Period 27.5.94 to 15.9.94.

	Volume	TP	FRP	TKN	NO <sub>2</sub> +NO <sub>3</sub>	NH <sub>3</sub> N	Pb
(a) Inflow concentrations (mg/L)							
Mean		0.18	0.11	1.68	0.44	0.35	0.014
SD		0.06	0.07	0.30	0.23	0.19	0.011
Min		0.10	0.00	1.03	0.08	0.07	0.002
Max		0.30	0.20	1.99	0.85	0.56	0.030
(b) Outflow concentrations (mg/L)							
mean		0.24	0.19	1.35	0.21	0.15	0.03
SD		0.09	0.06	0.18	0.04	0.05	0.102
Min		0.14	0.10	0.99	0.11	0.04	0.002
Max		0.46	0.27	1.57	0.28	0.20	0.37
(c) Inflow loadings; water (m <sup>3</sup> ), nutrients (Kg) and lead (Kg).							
Total	30388	4.91	3.14	48.31	12.77	8.90	0.54
(d) Outflow loadings; water (m <sup>3</sup> ), nutrients (Kg) and lead (Kg).							
Total	100493	25.18	19.19	136.43	21.00	15.43	2.07

Note. The source of data is the South Jandakot EMP Annual Report (Fuller & Deane, 1995). Inflow loadings (c) are calculated on the main inlet volume concentrations. The groundwater contribution is not included.

### ***Design Critique***

The commissioning of the Hird Road constructed wetland system has been premature. No specific design criteria exist for this wetland and the natural component of the wetland (Figure 4.9) is in private ownership with the discharge to land also under private ownership. Although zoning of the area is future urban development little consultation has occurred between existing land users and the relevant authorities. Due to the lack of design criteria it is not possible to conduct the critique in the same manner as was done for Bartram Road.

Site Location & Evaluation. The evaluation of site suitability or the collection of baseline data is absent for this wetland. Anecdotal history of the natural wetland suggests a likelihood of nutrient enrichment as a result of neighbouring land use, including piggeries and battery hens amongst other more general farm grazing. The leasee of the property cited the running of goats as the major cause in the degradation of the wetland vegetation. The northern edge of the wetland is adjacent to the farming area and Kikuyu grass dominates the banks. The southern edge has also been subject to disturbance due to the construction of a rising sewer main. This construction would have disturbed the natural sediments

and may have caused the release of nutrients to the water column. The works also removed fringing vegetation but there is some natural regeneration in the area. Anecdotal evidence on the flood regime of the wetland shows a significant increase in the volume and persistence of water. Previously the wetland would seasonally dry, however this has not occurred since urban development. Neighbouring land owners who receive discharge from the wetland have noted that the flooding in their lower paddocks has increased markedly since the wetland received stormwater discharge.

Surface Area & Aspect. The existing surface area constitutes 2% of the total catchment and about 5% of the proposed urban catchment. The aspect ratio of the main cell is effectively 3:1; even though the cell measurements are 80m x 340m the position of the inlet reduces the effective length by about 100m. The lack of ground water loading data to the system prevents an accurate estimate of surface area requirement based on inflow loading rates.

Storage & Treatment Volume. The storage capacity is estimated at 16000m<sup>3</sup>, however at least two thirds of that storage is groundwater. This estimation of groundwater input is derived from the difference between inflow and outflow volumes for the 93/94 sampling period (Table 2.7). This leaves a treatment volume of around 5000m<sup>3</sup>. Residence time based on the 93/94 inflow figures (Fuller & Deane, 1995) and converted to a histogram (Figure 2.3) showing the number of daily inputs that equal or exceed critical times for CRE (TSS, Nitrogen and Phosphorus respectively) suggest that the wetland should be effective in removing all forms of nutrients. The period covered by the histogram is June - September 1994 and corresponds to 121 daily inputs.

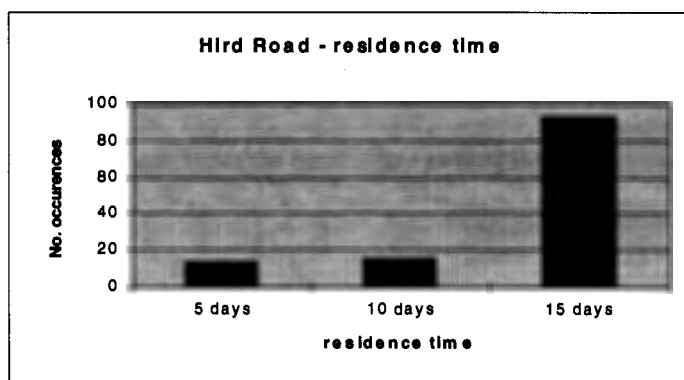


Figure 2.3. Histogram of theoretical residence time occurrences during June - September 1994 in the Hird Road catchment.



The imbalance in the nutrient budget (Table 2.7) shows a gross export of nutrients, contrary to the positive CRE indicated by the theoretical residence times. Four possibilities could explain this apparent contradiction. First, the significant input from groundwater is generating the nutrient export. Second, the wetland substrates are supersaturated with nutrients and act as a source of these pollutants. Third, the flow path is so significantly short-circuited that the wetland removal functions do not have the temporal requirement to be effective. The fourth possibility is a combination of the above effects. From available data the fourth possibility is the most likely. The flow data in Table 2.7 indicates a significant groundwater contribution while field assessments on nutrient retention and flow patterns conducted as part of this study, show high nutrient concentrations in the substrate (chapter 4) and short-circuiting of the flow path that is reducing theoretical residence time by a factor of between four and six (chapter 3).

**Basin Morphology.** Figure 4.9 shows the system having two cells with the smaller cell constructed and the larger cell a natural wetland. The purpose of the constructed cell is as an initial retention basin for sediment trapping. The flat cross-section and location within a formal park will enable easy access for maintenance equipment. The natural wetland has the desirable design features for constructed wetlands; the base is flat and appears to have minimal grade. This allows the assimilation of inputs through an increase in surface area rather than any significant increase in depth.

**Vegetation.** The vegetation planted on the surrounds of the retention basin is approximately 3m wide. There is no interspersed of the open water with vegetation. The natural wetland basin has a low vegetation to open water ratio (12%) but does have some remnant reed banks within the open water (Figure 4.9).

**Monitoring and Performance Evaluation.** Continuous dataloggers record flow and auto-samplers bulk two hourly samples for weekly analysis on the main inflow to Hird Road. Because the natural wetland is privately owned, no permanent sampling station has been established at the outflow. Outflow water quality assessment is achieved through regular manual sampling.

### ***Management Action***

Due to the lack of baseline data associated with the Hird Road Buffer lake stormwater treatment specific action is difficult to determine. It is critical that strategic and operational plans be developed for this system. This requires that immediate negotiations be entered into with the current landowners and that

a comprehensive baseline assessment of the wetland system be conducted at the earliest convenience. A review of the current structure should include the potential for relocating the retention basin to a position that will take advantage of the morphology of the natural wetland basin. In addition, this review should investigate the potential to incorporate a swale type, broad, flat and densely vegetated connection between the two basins.

In the short term, either the closing of the discharge drain or diversion of the stormwater input should be considered to prevent the high nutrient loads directly discharging to the Beeliar Wetlands. Should the decision be taken to purchase the land, planning needs to allow for a buffer strip surrounding the existing wetland area.

### **Bartram Road Buffer Lakes**

The Bartram Road constructed wetland is an end-of-line treatment system for stormwater runoff from urban development in the South Jandakot District. Urban zoning is 42% of this 10.5 km<sup>2</sup> catchment. The location is a modified natural wetland area west of Hammond Road and opposite the Bartram Road intersection in the Jandakot district (G B Hill & Partners, 1990 & 1991; Technical Review Committee, 1994).

### ***Performance Evaluation***

The constructed wetland system at Bartram Road became operational in August 1993. The report by the TRC (1994) on monitoring data for 1993 concluded that there was no significant difference between inflow and outflow concentrations. Preliminary analyses of monitoring data for 1994 (Fuller & Deane, 1995) show large variations in CRE, with seasonal CRE in the range of -4.79% for filterable reactive phosphorus to 43% for nitrite and nitrate. Table 2.8 tabulates a summary of CRE performance for Bartram Road constructed wetland for the period 26.5.94 to 14.10.94. The periods of minimum and maximum CRE correspond to maximum and minimum flows respectively.

The primary objective of the Bartram Road constructed wetland is a 30% reduction in Phosphorus concentration of outflow to Thomsons Lake. That objective is not being achieved. Literature suggests that establishment of vegetation within the system is necessary before constructed wetlands can achieve CRE performance objectives. This may involve a lag time of up to five years. However, the Bartram

Road system has substantial areas of well established and dense stands of existing wetland vegetation. In addition, three of the wetland cell structures incorporated red mud to offset that lag time in CRE.

Table 2.8. Nutrient Retention and CRE for Bartram Road for the period 26.5.94 to the 14.10.94.

	TP	FRP	TKN	NO <sub>2</sub> +NO <sub>3</sub>	NH <sub>3</sub> N
CRE as Kgs retained in wetland	12.09	-10.21	90.91	46.74	11.71
CRE mean % change in flow conc.	4.38	-4.79	6.39	43.47	19.00
Range of CRE as a % change in flow conc.	-21 to 70	-28 to 67	-48 to 85	-30 to 91	-54 to 83

Note. (Table 2.8) The data were derived from the Report No. PSWRS051 South Jandakot Buffer Lakes 1993/94 Monitoring (Fuller & Deane, 1995). The negative values in %'s indicate an increase in outflow concentration compared to inflow whilst negative load retained indicates the wetland is acting as a source of the contaminant.

### ***Design Critique***

The design criteria established in the previous section is the basis for the following critique of the design process for Bartram Road. Figure 4.15 describes the physical parameters of the Bartram Road constructed wetland.

Stormwater Treatment Strategy. The consultant's report (G B Hill & Associates, 1990 & 1991) was thorough and concluded that the use of constructed wetlands would mitigate the stormwater impacts of proposed urban development on Lake Thomson and the Beeliar Wetland chain. It is relevant to note that the report emphasised the CRE of the proposed wetlands related to the removal of particulate matter and not pollutants in dissolved forms.

Design Objective. The primary objective is a thirty per cent reduction in phosphorus concentration in the constructed wetland inflow concentration. Literature suggests that the objective is achievable and is conservative. The storage capacity and evapotranspiration of the wetland will achieve the secondary objective of reducing the volume of runoff to Thomsons Lake.

Stormwater Properties. Computer modelling of runoff volumes determined the treatment volume for the constructed wetland. An analysis of inflow for the 1994 winter season shows that nutrients, phosphorus in particular, is pre-dominantly in dissolved form. Up to 75% of phosphorus is present as FRP (Tables 2.2 & 2.9). However, the design of the wetland is predicted on nutrients being in particulate form. In the case of Bartram Road the particulate matter constitutes a relatively small proportion of the contaminant load. The other relevant property of the runoff is that it is highly coloured. This can result

in reduced levels of photosynthesis and a corresponding reduction of CRE due to floating or emergent vegetation.

**Site Location and Evaluation.** The site for the buffer lakes consisted of approximately 50% natural wetland area. The vegetation community consisted of dense stands of *Baumea articulata* with associated reeds and sedges, and fringing stands of *Melaleuca* and *Eucalyptus rudis* (Figure 4.15). The 6.2 ha site was excised from an existing riding school and horse breeding farm. Local anecdotal history cites part of the area being used as a rubbish disposal tip, a burial area for horses and as part of riding trails. In addition the stables and paddocks drained into the swamp area. Foraging by stock is probably responsible for the lack of understorey in the flooded gum areas. No pre-construction substrate analysis was conducted in what was probably a nutrient enriched wetland.

Table 2.9. Bartram Road Summary of Water Quality Monitoring for the Period 26.5.94 to the 14.10.94.

	Vol	TP	FRP	TKN	NO <sub>2</sub> +NO <sub>3</sub>	NH <sub>3</sub> N	Pb
(a) Inflow concentration (mg/L)							
Mean		0.47	0.35	2.48	0.18	0.10	0.059
SD		0.15	0.16	0.49	0.10	0.05	0.138
Min		0.21	0.11	1.54	0.04	0.05	0.002
Max		0.67	0.56	3.32	0.36	0.27	0.34
(b) Outflow concentration (mg/L)							
Mean		0.49	0.40	2.37	0.09	0.10	0.002
SD		0.14	0.10	0.35	0.05	0.05	0
Min		0.32	0.22	1.76	0.04	0.05	0.002
Max		0.99	0.61	3.11	0.25	0.31	0.002
(c) Inflow Loadings; water (m <sup>3</sup> ), nutrients (Kg) & Lead (Kg).							
Totals	558332	273	210	1407	106	61	
(d) Outflow loadings; water (m <sup>3</sup> ), nutrients (Kg) & lead (Kg).							
Totals	547265	264	223	1331	61	50	

**Note.** Lead loadings have not been calculated because several recordings were at or below detection limits. It is of note that one sample (1.6.94) had a concentration of 0.34 mg/L. The data were derived from the Report No. PSWRS051 South Jandakot Buffer Lakes 1993/94 Monitoring (Fuller & Deane, 1995).

**Storage Capacity & Residence Time.** The estimated maximum storage capacity of Bartram Road constructed wetland is 49110 m<sup>3</sup> (chapter 4). Fuller & Deane (1995) supplied continuous hydrological data for Bartram Road which can be used to assess the storage and residence time design of the wetland. Converting the flow data for June - September 1994 to a histogram of residence time (Figure 2.4) based on the formula in the previous section suggests that the wetland should have been effective in TSS removal (>3 days), dissolved nitrogen transformation (10 days) and dissolved phosphorus removal (15 + days). However this was not the result of CRE evaluation for 1994 (Table 2.8). Flow trials conducted

during July 1995 indicate that short-circuiting of the flow path is significant and may result in a reduction of theoretical residence time by a factor of four (chapter 4). Such a reduction in the theoretical residence times would account for the poor CRE of Total Phosphorus.

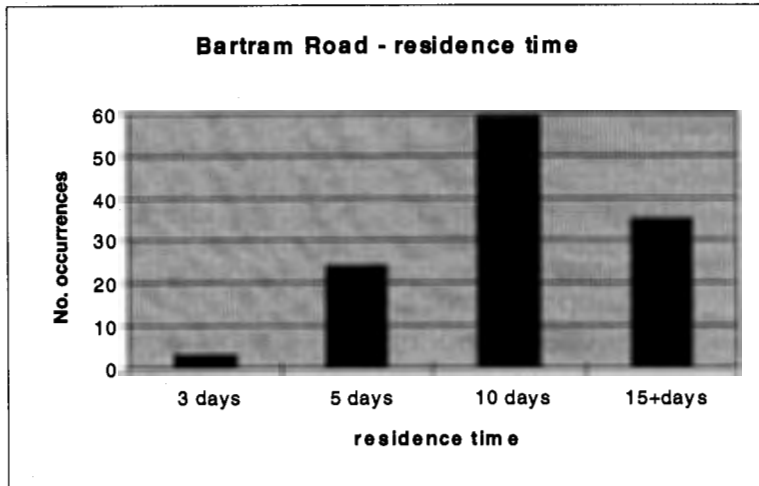


Figure 2.4. Histogram of theoretical residence time occurrences in the Bartram Road catchment from June - September 1994 (Fuller & Deane, 1995).

There has been no evaluation of the ground water contribution to the water budget of the system. The system had water flow from cell 4 to cell 5 and to the outlet before any observed flow between cells 3 and 4. This indicates a ground water contribution that could significantly reduce the treatment storage capacity of the system.

It is expected that the particulate composition of the inflow will increase with the increase in urbanisation planned for the Bartram Road catchment. However, on current figures, the increase in urbanisation will also result in an increase in runoff volumes reducing residence times.

**Basin Morphology.** The complex five cell design should enable a variety of wetland removal functions. However the method of construction restricts the functional capacity to five individual wetlands. The cells are inter-connected by either culverts or narrow open drains. This has the effect of channelling the water flow and results in remixing of the water column in each of the cells. The continual mixing of the waterbody can make CRE determination difficult as the waterbody is subject to varying dilutions and its resultant exposure to wetland removal functions is inconsistent.

The constructed basins in this system are cells 1,2 & 5. The design of the cells incorporated "V" cross-section that has a "red mud" lining. The purpose of the "V" sections was to allow gradual inundation of

planted fringing vegetation but this strategy is counterproductive; channelisation of the water column occurs and reduces residence time in the cell. The variation in depth that results from the section means that the water column does not become exposed to the same water-soil-vegetation interactions.

Research into “Red mud” shows it to be effective in increasing phosphorus adsorption from the water column (Sampson, 1994). However its use is subject to critical design factors. Observations of red mud at the site showed that this material; on the banks was easily eroded and washed into the basin, on the basin floors it was easily resuspended and did not settle quickly whilst coring of the red mud lined cells indicated that the material clotted, forming very hard impervious layers (chapter 4). These observations are similar to findings by Sampson (1994). The disadvantages of red mud may outweigh its phosphorus retention potential.

The aspect ratios of cells exceed the minimum recommended requirement of 2:1. The “rule of thumb” 3-5% surface area requirement of the catchment is met only if the proposed urban area of 50 ha is used as the catchment. The surface area of the buffer lakes (3.2 ha) constitutes less than 1% of the total catchment of 1050 ha (Deane et al., 1994). A more accurate measurement of surface area requirement is based on the desirable loading rates of 5g P/m<sup>2</sup>/yr and 25g N/m<sup>2</sup>/yr for optimum CRE of the nutrients. Using this criterion, and applying known loading rates for the constructed wetland system (Fuller & Deane, 1995) a surface area of 5.5 to 6 ha is required. This is almost twice the existing surface area for the Bartram Road system.

Vegetation. The constructed wetland has extensive areas of natural vegetation. Cells 3 & 4 (Figure 4.3) have the desired high density vegetation cover (> 70%). These cells constitute the surviving natural wetland area. However, construction techniques have reduced their effectiveness. *Baumea* removed from cell 4 for transplantation in cells 2 & 5 unfortunately resulted in a strip of open water on the north side of the bund constructed in cell 4. This has permitted water flow from cell 3 into cell 4 to channel and short circuit this densely vegetated cell. This short-circuiting was apparent during tracer dye trails conducted on this wetland in July 1995 (chapter 4).

Vegetation cover is less than 10% of the water surface area in cell 1. This consists of fringing macrophytes and there is no interspersions of the open water. This is consistent with the purpose of the cell - slowing the water flow and trapping sediment. However, this design does not meet all the

requirements for maintenance and sediment removal. Access for heavy maintenance equipment to perform these functions are not available. Planted sedges and reeds at the high water line in cells 3,4, and 5 are unlikely to play a direct role in water quality improvement. However, they contribute to vegetation community complexity and assist in bank stabilisation.

The design purpose of *Baumea* transplanted perpendicular to the flow path in cells 2 and 5 was to reduce flow velocity and assist in particle entrapment. This transplantation has not been particularly successful. There are two inter-connected causes for this failure. First, the 'V' section of the basins causes higher flow velocities to occur in the deepest section where the plants are under most stress. Second, the red mud surrounding the transplanted *Baumea* presents a more resistant surface than the soft peat accompanying the *Baumea*. The result was that the peat eroded and the *Baumea* dislodged before it could become established in the new location. Poor vegetation-open water interspersed characteristics are now apparent in these cells.

Substrate. A preliminary survey of the wetland showed that the soils in cells 3 and 4 are organic. It is possible that the construction of the sewer line and the modification of the wetland during the buffer lakes project may have disturbed nutrient rich sediments permitting their release to the water column. Three cells have red mud amended soils (Figure 4.15) with the intention of increasing the wetland capacity to retain phosphorus. However, as referred to in previous sections this type of substrate has detrimental effects on vegetation establishment, clogs and is easily eroded.

Monitoring and performance evaluation. The system has a comprehensive water quality monitoring programme that includes continuous flow data loggers and auto samplers located at the inflow and outflow points. However, as the EMP only requires annual reporting on these data, this can result in required management action having a lag time of more than one year. Also, there has not been an assessment of the structure and function of the system to date and there is only minimal baseline data for future assessments. This shortfall in the evaluation programme will make active management decisions difficult. Operational guidelines for the buffer lakes' management do not exist.

### ***Management Action***

The Bartram Road constructed wetland requires modifications to the existing design to achieve a higher CRE performance. The modifications range from relatively minor to extensive:

- revegetate the channel area of the north side of the central bund in cell 4. *Baumea* on the south side of the dividing earth bund between cells 3 and 4 could be transplanted. Relatively small clumps should be selected intermittently to prevent the possibility of creating a channel that may result in short-circuiting;
- increase the vegetation density and reduce the interspersed characteristics of cells 3 and 5. That is, at least ensure that open water is not continuous from inlet to outlet. This should be conducted in conjunction with the following;
- review the V- section to cells 2 and 5, converting these basins to a flat base;
- review the culvert and narrow drain connections between cells. Although modification options are limited due to the sewer line, significant gains in performance are possible by incorporating cells 2 and 3, and cells 4 and 5. This would involve the re-design of cell 2 and major works to construct a swale drain connection to cell 3. Cell 2 would become a shallow, densely vegetated basin. Similar works would create a swale or densely vegetated shallow and broad connection between cell 4 and cell 5.

In addition, it is recommended that interim water quality reports be compiled monthly during the wet season (June-September). The wetland structure also requires assessment on a regular basis. It is recommended that an assessment programme similar to that outlined in chapter 4 be adopted.

### **Case Study Summary**

Each of the constructed wetland sites examined failed to meet all of the design criteria established in the previous section. Tabulating the criteria against the respective wetland design (Table 2.10) showed Bartram Road the theoretically more effective system. This is supported in field assessment studies on CRE at the wetland sites in August 1995 (chapter 4). The residence times noted in Table 2.10 are theoretically based. The actual residence time for Bartram and Hird may be a factor of four less than the theoretical (chapter 3) and this may mean the wetlands would not meet a minimum three day residence time for runoff from 90% of annual storms.



Given that none of the constructed wetland systems appear to be consistently meeting design objectives and do not comply with all of the compiled design criteria, infers the relevance of the compiled criteria to constructed wetland systems.

Table 2.10. Case study comparison of Bartram, Hird and Russell constructed systems against theoretical design criteria.

Design Parameter	Russell Street	Hird Road	Bartram Road
Surface Area ratio (3-5%)	N	total catchment - N urban catchment - Y	total catchment - N urban catchment - Y
Storage (90% storms)	N	Y	Y
Min. 3 day R/T on 90% of storms.	N	Y	Y
Min. aspect 2:1	Y (unless island inundated)	Y	Y
Nutrient load to surface area.	data unavailable	data insufficient	N
Vegetation to open water ratio	low	low	moderate
“gentle” batters (> 1: 6)	N	N - constructed cell Y - natural wetland	in limited areas
basin design to avoid channels	Y	N	N
Substrate amelioration	N (mineral sand)	N (includes natural peat areas & sand)	Y (red mud also natural peat areas)
System complexity	simple	moderate (2 cells)	complex (5 cells)
Pre-project assessment	N	N	partial
Compliance audit	N	N	N

## ***Role of Constructed Wetlands in Urban Stormwater Management***

In considering the role of constructed wetlands in urban stormwater management it must first be accepted that urban stormwater runoff is a significant source of pollution that must be addressed. The

most logical method of addressing the problem is removal of the source. Guidelines for water sensitive urban designs are reducing the problem in newly established urban areas, however their acceptance by local authorities and developers has been slow mainly due to the increased site works required. Not all urban areas can be adapted in this way and those drainage systems require an alternative strategy. Treatment of stormwater in an end-of-line system is expensive and will have some impact on the local environment regardless of the strategy used. Again, regardless of the strategy, end-of-line treatment requires a commitment to extensive monitoring, performance evaluation and reporting to allow active management to minimise potential impacts on receiving environments. For these reasons end-of-line treatment must be held as a last resort option.

Should in-line or end-of-line treatment of stormwater be the only management option available then an analysis of the advantages and disadvantages of using constructed wetlands are required before adopting the strategy. The following resumé of the advantages and disadvantages are presented in general terms.

### **Disadvantages of Constructed Wetlands for Stormwater Treatment**

The disadvantages of constructed wetland systems are economic considerations and the uncertainty of performance. Although cheaper to maintain, they can require extensive land area to be effective. Availability of land and the capital cost of acquiring that land represent the major barriers. Construction costs of earthworks and planting are less than that required for the structure of conventional treatment works. Uncertainty of performance concerning contaminant removal is inherent in the use of natural systems and the precautionary principle applies to counter the inexact science of constructed wetland design. The design flexibility needed to overcome this uncertainty adds to the extensive land area requirement of wetland systems. Conventional treatment systems have similar disadvantages but few of the advantages of constructed wetland treatment systems.

Just as critical are the potential problems that can arise from inappropriate design or maintenance of constructed wetlands. Wetlands provide breeding grounds for biting insects that can be vectors of serious disease or present a nuisance risk to human populations. Other nuisance factors include habitat for poisonous snakes, increased fire risk, weed and feral animal invasion. Active management programmes can control and reduce these nuisance levels to acceptable community standards. However, wetland managers must be able to demonstrate effective mosquito population control. The increasing

incidence of local and exotic insect-transmitted disease and their immunity to known medicines is a problem of national concern. This problem has the potential to limit widespread establishment of constructed urban wetland treatment systems (Kentula et al. 1993; Knight, 1993; Mitsch & Gosselink, 1993; Olson, 1993).

The ability of wetlands to act as contaminant sinks may also have long term health and performance implications. To a large extent this remains an unknown element of wetlands. Elements that require monitoring are sedimentation, accumulation of heavy metals and saturation levels of nutrients in wetland components (Erwin, 1990; Guntenspergen, Keough & Allen, 1993; Knight, 1993; Olson, 1993; Tchobanoglous, 1993). Conventional treatment systems also face similar problems in the disposal of accumulated waste products.

### **Advantages of Constructed Wetlands for Stormwater Treatment**

The reward for achieving a viable and sustainable wetland for stormwater runoff treatment is a facility that is multi-purpose and has many advantages over conventional water treatment plants.

The advantages apply to all aspects of the environment. The natural environment benefits from a system that is a viable and sustainable utilisation of natural resources. Successful wetland treatments are more cost effective than conventional treatment plants (Knight, 1993; Olson, 1993). There is a reduction in ongoing costs of water treatment and water quality improvement is higher than in conventional systems (Evangelisti, 1994).

Successful constructed wetland systems have the potential to become multi-use facilities. Whereas the primary objective must always be the mitigation of stormwater runoff impacts, the constructed wetland facility offers important anthropocentric advantages. The establishment of constructed wetlands through the process of ICM encourages a sense of community while other ancillary benefits include: landscape enhancement; wetland habitat creation; recreational use; and the education and research of wetland functioning (Bowmer & Bales, 1992; Diessner, 1992; Evangelisti, 1994; Knight, 1993; Hopkins & Argue, 1992; Pen, 1994).

In conclusion the most critical element of constructed wetland design is the realisation that natural processes are uncompromising. The constructed wetland will adapt to the prevailing conditions and

they will not perform the desired contaminant removal function unless ALL the required elements are present ALL the time. Perhaps the major contributor to poor performance is the compromise on storage and area requirements. These two elements are integral to the nutrient loading capacity of the wetland which appears to be a neglected item within constructed wetland planning. This is reflected in the CRE performance of a constructed wetland system that may not be meeting design objectives but is performing to design elements. That is, the constructed wetland system will remove the amount of pollutants from waterbodies that the actual components of the system are capable of assimilating in one form or another.

## **Chapter 3**

# **Rhodamine WT Tracer Dye Studies**

*Determination of flow regime, concentration contours and residence time for the Bartram, Hird and Russell Constructed Wetlands.*

## ***Introduction***

The literature review on functions and design elements has emphasised the importance of wetland hydrological cycles to the functioning and structure of wetlands. The design for CRE is largely dependent on the residence time of inflow water. Theoretically, the residence time is calculated by dividing the wetland storage by the inflow volume per day. This assumes that the flow pattern of the wetland closely approximates a plug flow regime. That is, inflow volume displaces the standing water and is in turn displaced by following inflows. The inflow volume then moves through the wetland as a 'body of water' with minimal dispersion or mixing with the standing water. The hydrological studies by Kadlec et al.(1993) on three wetlands in America show that this plug flow theory is unrealistic in that it is rarely achieved in natural situations. Short-circuiting of design flow paths during severe storm events cited by Esry et al. (1989), Meiorin (1989) and Reuter (1991) suggests that the flow pattern within wetlands will vary according to inflow volumes. Despite the findings of these studies the flow regime of constructed wetlands is designed as plug flow with residence time being a direct mathematical relation between inflow volume and storage volume.

The purpose of the Rhodamine WT tracer dye trials was to compare actual flow regimes at the study sites with the theoretical regime. The initial study conducted Rhodamine WT dye trials in Bartram Road, Hird Road and Russell Street at staggered intervals to enable flow to be analysed during the same rainfall event. This trial revealed that the theoretical regime was markedly different to the actual hydrological regime in all three constructed wetlands. The trial methods were modified and then repeated at Russell Street and at Hird Road to verify the results of the first trial. Unfortunately, a shortage of Rhodamine WT dye excluded replication trials at Bartram Road.

## **Methodology**

The trials labelled a body of inflow water with Rhodamine WT dye and tracked its movement through the wetland. Rhodamine WT was chosen as the tracer dye due to its inert, highly stable and low adsorption characteristics. The dye has proven to be an effective tracer in sewerage flow studies and wetlands (Kadlec et al., 1993; Pilgrim et al., 1993; Turner Designs, undated).

### **Establishing Recovery Ratios of Rhodamine WT**

Although Rhodamine WT has low adsorption characteristics, particulate matter that is high in carbon content can result in low recovery ratios (Turner Designs, undated). This problem is offset by filtering the samples before fluorometric analysis if it is found that the flow contains matter high in carbon content.

Preliminary sampling was required to establish whether the water from the three wetlands would require filtering before fluorometric analysis. The recovery ratio was determined by comparing fluorescence of standards at the same concentration of Rhodamine WT but prepared from DDI water and influent from the respective wetland.

$$\text{Recovery Ratio} = \frac{\text{Standard (sample 0.5ppm)}}{\text{Recovery Standard (DDI 0.5ppm)}}$$

Turner Designs (undated) cite an accuracy of +/- 5% and +/- 2% for recovery ratios of 0.9 and 0.95 respectively. The recovery ratios for Bartram Road, Hird Road and Russell Street were 0.9, 0.91 and 1 respectively. The estimated accuracy of results for unfiltered samples at Bartram and Hird was +/-5% and for Russell Street +/-2%. This accuracy level was acceptable for the planned trials and water samples taken during the trials were analysed unfiltered.

### **Labelling of Water Body**

At each wetland site the concentration of Rhodamine WT to one cubic meter was determined so that the dye concentration only minimally exceeded 0.5ppm but would remain at detectable levels through the wetland if the labelled water completely mixed with standing waters. A maximum concentration of 0.5ppm was desirable because fluorometer readings below that concentration enable a linear regression analysis to determine sample concentrations (Turner Designs, undated). The 0.5ppm desirable concentration level reduced the need to perform dilutions on samples.

The initial trial labelled one cubic meter of inflow water with 500 ml, 200 ml and 100 ml of Rhodamine WT at Bartram Road (storage volume estimated at 50000 m<sup>3</sup>), Hird Road (storage volume estimated 22000 m<sup>3</sup>) and at Russell Street (storage volume estimated at 10000 m<sup>3</sup>) respectively. The concentration of the labelled water was 500ppm, 300ppm and 100ppm respectively.

The labelling of the one cubic metre of inflow was achieved by establishing the flow rate and adding the required Rhodamine WT at a constant rate over the time taken for one cubic metre of inflow to pass the mixing station.

$$\text{Flow rate} = \text{flow velocity} \times \text{cross section area of inflow.}$$

Culverts upstream of the constructed wetlands were selected as mixing stations. These points afforded a determinable cross section point and enabled the dye to thoroughly mixed with the water column before entering the wetland. The flow velocity was measured using the Marsh McBirney Model 201 portable water current meter. An error in the calculation of cross sectional area for Hird Road meant only 0.66m<sup>3</sup> of inflow was labelled, hence the concentration of 300ppm instead of 200ppm.

The replicate trial at Russell Street used the same method of labelling the water column as the initial trial. However the concentration was increased to 500 ppm by adding 500 ml of Rhodamine WT to one cubic meter of inflow.

The Hird Road replicate trail was modified to track the labelled waterbody through cell 2 (Figure 4.9). This involved pegging out an area at the inlet to cell 2 estimated to hold five cubic meters of water. Ten (10) ml of Rhodamine WT was thoroughly mixed to the water column to achieve a concentration of 2ppm for the labelled water.

### **Weather Conditions and Inflow Volumes**

Rainfall was recorded using a standard rain gauge located on site. During the initial trial the gauge was located at the Bartram Road site. During the second series of trials, the gauge was located at Russell Street and Hird Road respectively. Inflow and outflow volumes for Hird and Bartram wetlands were obtained from WAWA datalogers located at each site. The initial trial at Russell Street did not have flow volume information. During the replicate series of trials, volumes at Russell and Hird were determined by flow velocity and depth measurements at known cross-section points. Measurements

taken at Bartram Road and Hird Road were used to establish the accuracy of volume determination against the continuous flow data supplied by the WAWA (Fuller & Deane, 1995). This comparison showed that the method used in these trials calculated volumes within +/- 10% of those from the continuous flow recorders.

The flow data was used to calculate theoretical residence times and the actual proportion of labelled water discharged. Rainfall figures were compared with meteorological data to establish the occurrence frequency.

### Sampling for Rhodamine WT

Sampling locations at each wetland were selected to establish the distribution and flow pattern of the labelled water. The sampling locations are shown in Figures 3.3, 3.4, 3.6, 3.7, 3.8 & 3.9. Table 3.1 shows the date, sampling periods and the number of samples taken at each period.

Table 3.1. Sampling period, intervals and number of samples for the Rhodamine WT tracer dye trials at Bartram Road, Hird Road and Russell Street constructed wetlands.

Wetland	Sampling Period	Sampling Intervals (hours after dye injection)	No. of Samples per Interval.
Bartram Road	19.7.95 to 24.7.95	1, 3, 6.5, 11, 25, 34, 49.5, 75.5, 99, 125.	37
Hird Road (1)	19.7.95 to 24.7.95	1, 4.5, 19, 28, 46, 72, 96, 120.	14
(2)	8.8.95 to 10.8.95	2, 4, 12, 20, 24, 30, 48.	11
Russell Street (1)	20.7.95 to 23.7.95	1, 3, 8, 21, 31, 48, 72.	11
(2)	29.7.95 to 31.7.95	1, 2, 6, 8, 10, 24, 34.	11

Water samples were collected in numbered Fluorometer cuvettes. The cuvette number was recorded against the location and sampling time. To prevent sediment disturbance inferring with the sample, sample locations were approached from a downstream position. The cuvettes attached to a 2m pole enabled sampling away from any disturbance caused by the sampler. The same order of sampling was maintained throughout the trial period.

The samples were transported to the laboratory at convenient times through the trial period. As analysis was performed at room temperature and the dye is a stable compound no special storage was required.



### **Fluorometer Analysis of Rhodamine WT Samples.**

A Series 10 Turner Fluorometer calibrated for Rhodamine WT analysis used to determine water sample Rhodamine WT concentration was located at the Marine and Freshwater Laboratory, Murdoch University. The analysis was performed according to procedures set out in the Operating and Service Manual; Model 10 series Fluorometer. (Turner Designs, 1976).

Fluorescence of Rhodamine WT has a temperature coefficient of -2.6% per degree centigrade and so it was critical the analyses were performed at constant temperature. The samples and standards were allowed to stand at room temperature for a minimum of thirty minutes. Random checks were conducted throughout the analysis by re-running samples at various times. The standards were routinely run at the start and finish of each run. By observing the minimum thirty minute climatisation period, no problems with temperature variation were experienced. In addition blanks were prepared from influent taken before the commencement of the trial and were used to determine background interference affecting detection levels.

Three sets of standards were prepared using inflow waters from each wetland. The standards were 0.5ppm, 0.25ppm, 0.1ppm and 0.05ppm concentration. Given that a 1% solution of Rhodamine WT is at 10000ppm (Turner Designs, undated) serial dilution was used to prepare the standards from a 1ppm stock solution.

### **Data Analysis**

#### ***Rhodamine WT Concentration***

The Fluorometer readings for each sample were entered into a Excel 5 spreadsheet. Standard curves were constructed from a regression analysis of the fluorescent values for the standard solutions. The error of regression analysis was adapted from Fowler & Cohen (1992) to the Excel spreadsheet. Sample fluorescence was then converted to Rhodamine WT concentration in ppm from the standard curves. The calculated concentration for the blanks established the minimum detectable level for Rhodamine WT within each constructed wetland.

#### ***Flow Type & Residence Time***

A graph of outflow Rhodamine WT concentrations against time illustrates the labelled waterbody flow type. A narrow parabolic curve indicates a plug flow regime whereas a tapering curve or a constant line

indicates a well mixed water column. The percentage of labelled water discharged during various sampling intervals was calculated as:

$$\% \text{ discharge} = \frac{\text{Volume Out } (t_1 - t_2) \times \text{Mean Conc } (t_1 - t_2)}{\text{Volume}_{(\text{label})} \times \text{Conc}_{(\text{label})}} \times 100$$

where; conc = ppm of Rhodamine WT,

$(t_1 - t_2)$  = time interval over which the discharge volume and concentration has been determined and

label = the original volume and concentration of the body of water labelled with Rhodamine.

The residence time of the labelled waterbody was calculated as  $(t_1 - t_2) = 100\%$  discharge.

Where the labelled water was still present at the conclusion of the trial, residence time was estimated from outflow volume and derived concentrations to achieve 100% label discharge.

### ***Distribution & Flow Pattern***

For each wetland and each time interval the sample dye concentrations were plotted on site plans.

Concentration contours were then manually interpolated. The concentration contours indicate the distribution and flow pattern of the labelled water through the wetland.

## ***Results***

### ***Analysis***

High minimum detection levels and corresponding higher standard error in Bartram and Hird wetlands were due to the strong colour present in the inflow water (Table 3.2). This did not present significant problems to the concentration contours or residence time analysis.

Table 3.2. Error of regression and detection limits of Rhodamine WT at Bartram, Hird and Russell wetlands.

	Bartram Road	Hird Road	Russell Street
Standard Error of the regression (ppm)	0.01	0.01	0.006
Detection Limit (ppm)	0.04	0.03	0.01

### Russell Street Flow Regime, Resident Time & Concentration Contours

The rainfall during the first trial period from the 20.7.95 to 24.7.95 was a total of 41mm. This represented a storm event at the 85 percentile of all storm events for thirty-seven years. The return interval for such a storm is estimated to be quarterly (Evangelisti, 1994). No flow volumes were measured during this period. The residence time of labelled water for this trial was estimated between twenty-one and thirty-one hours (Figure 3.1). The pattern of flow approximated plug flow regime with a rapid rise and decline in Rhodamine WT concentration detected at the discharge structure (Figure 3.1). The plug flow was also apparent in the concentration contours during the early sampling intervals (Figure 3.3a.). The ability of the central island to direct flow and extent the flow path was also apparent at this time. The fringing vegetation appeared to retard the flow of labelled water with Rhodamine WT detected only at locations close to vegetation areas at eight and twenty-one hour intervals (Figure 3.3b). No Rhodamine WT was detected at the thirty-one, forty-eight or seventy-two hour sampling. The plot of concentration contours suggested that the majority of labelled water discharge was between the three hour and twenty-one hour sampling intervals (Figure 3.3 a-b). Given that the rainfall event was within that recommended for design volume calculation (chapter 2) the resident time of twenty four hours was significantly less than the design objective of five days. During the trial the central island was inundated for a period between the eight and thirty-one hour sampling. However the sampling intervals did not appear to show the effect of this change to the hydrological regime. To establish whether this was an unusual event the trial was replicated on the 29.7.95.

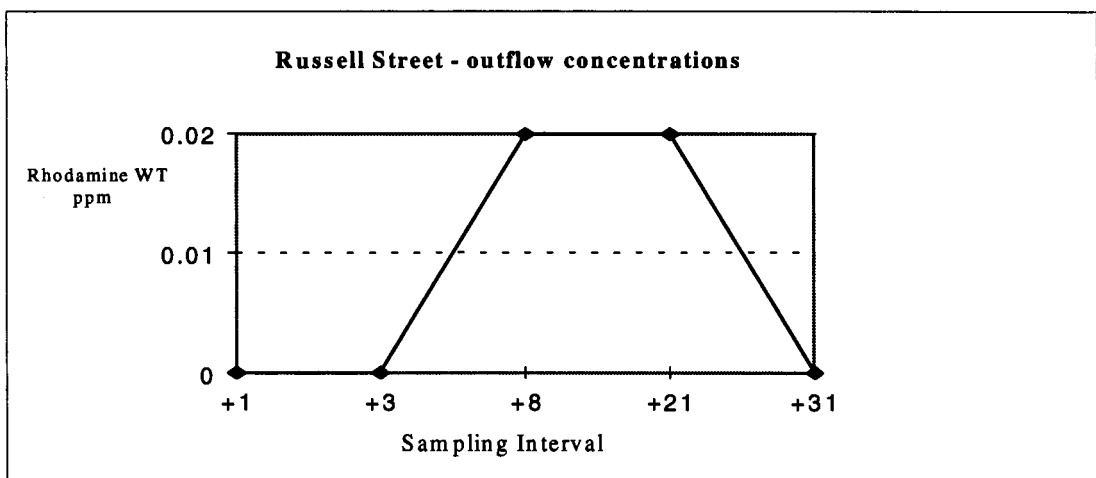


Figure 3.1. Russell Street Biofilter. Outflow dye concentrations for the sampling intervals during the initial trial conducted between 20-23.7.95.

During the replicate trial the storage capacity was near maximum with outflow depth of discharge peaking two hours after the commencement of the trial. The rainfall for the sample period was a total of 11mm representing a storm event in the 50 percentile with a return frequency of fourteen days (Evangelisti, 1994). The central island was inundated at the commencement of the trial causing broad dispersal of the labelled waterbody on contact with the standing water (Figure 3.4a). However the flow pattern following the initial dispersal was similar to the initial trial. The flow regime approximated plug flow only in that it peaked. Concentration of Rhodamine WT gradually declined after the peak at four hours to zero at thirty-four hours (Figure 3.2). The residence time for the two trials appeared similar (Figure 3.1 & 3.2) however when calculating the per cent discharge of the labelled waterbody for each sampling interval fifty per cent had been discharged after six hours and ninety-eight per cent after twenty-four hours (Table 3.3). The reduction in volume discharged between the six and twenty-four hour sampling appears to be the effect of the fringing vegetation retarding the flow of the labelled waterbody (Figure 3.4 b-d.).

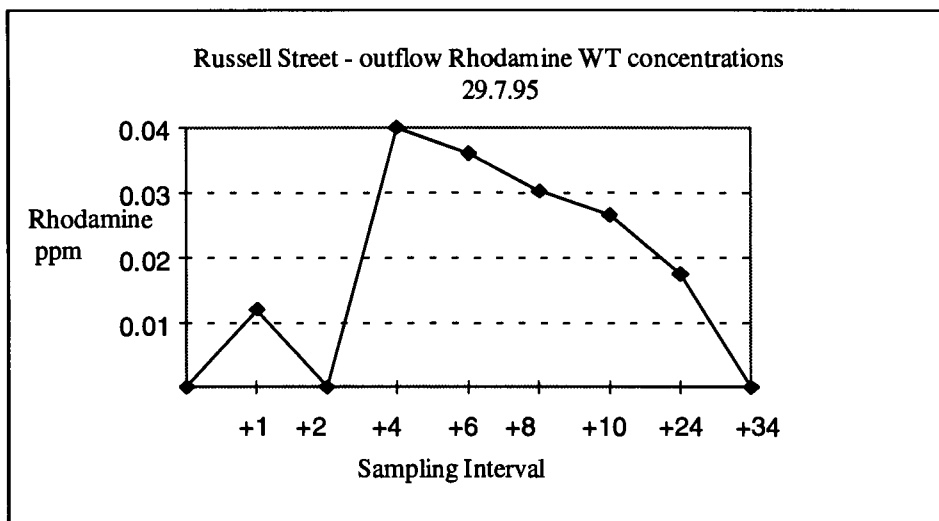


Figure 3.2. Russell Street Biofilter. Outflow dye concentrations at sampling intervals during the replicate trial 29-30.7.95.

Table 3.3. Accumulative labelled waterbody discharge during the Russell Street replicate trial conducted 29.7.95 to 30.7.95. Outflow discharge volume listed is that for each sampling interval.

Sampling Interval							
(hrs)	+1	+2	+4	+6	+8	+10	+24
outflow conc.- (ppm)	0.01	0.0	0.04	0.03	0.03	0.03	0.02
Volume discharge (m <sup>3</sup> )	1300	2613	3569	2635	2635	2350	4612
% labelled water discharged	3	3	32	53	69	82	98

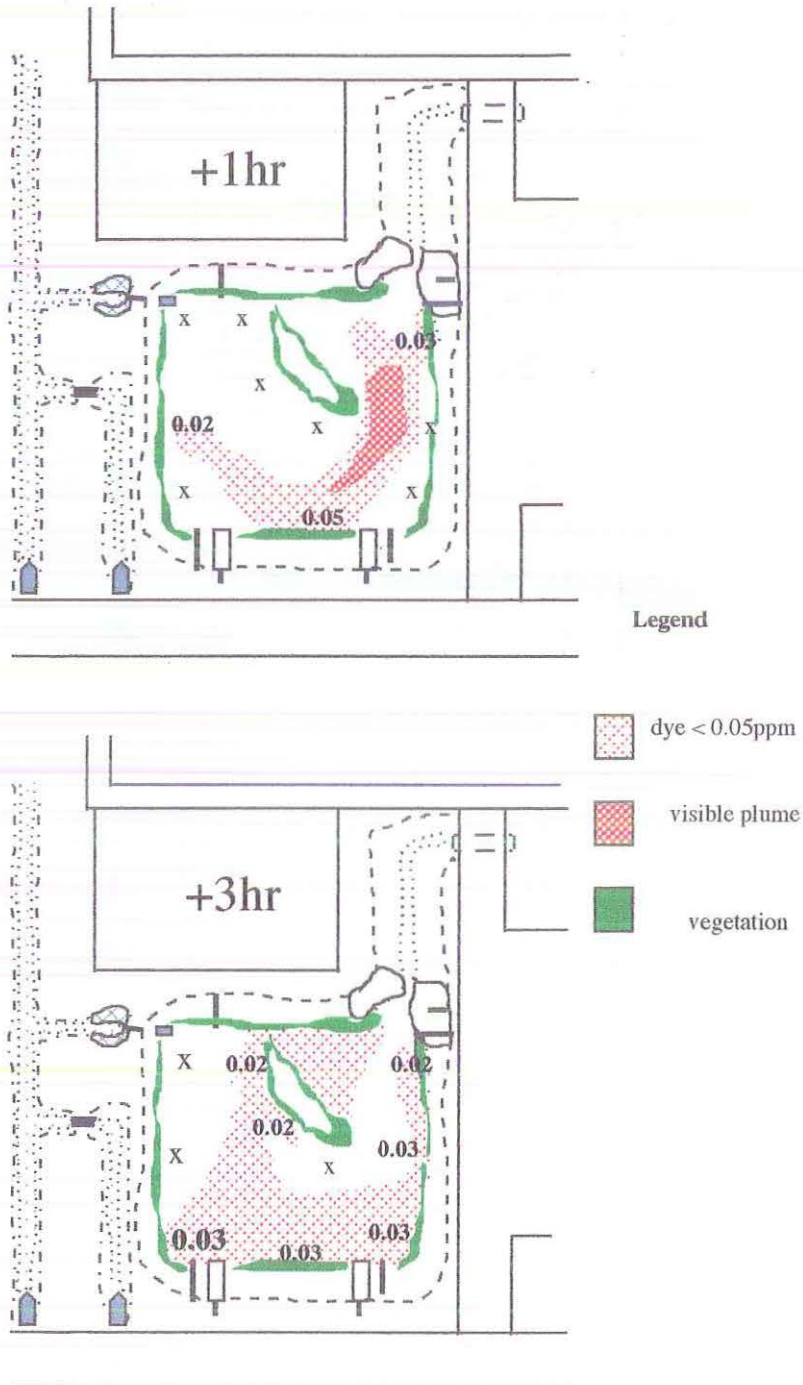


Figure 3.3. (a) Russell Street Rhodamine WT Tracer Dye Trail conducted on the 21.7.95. The extend of mixing of the labelled water is shown at 1and 3 hour intervals from the time of dye injection. The labelled water was still visible 1 hour after the injection.

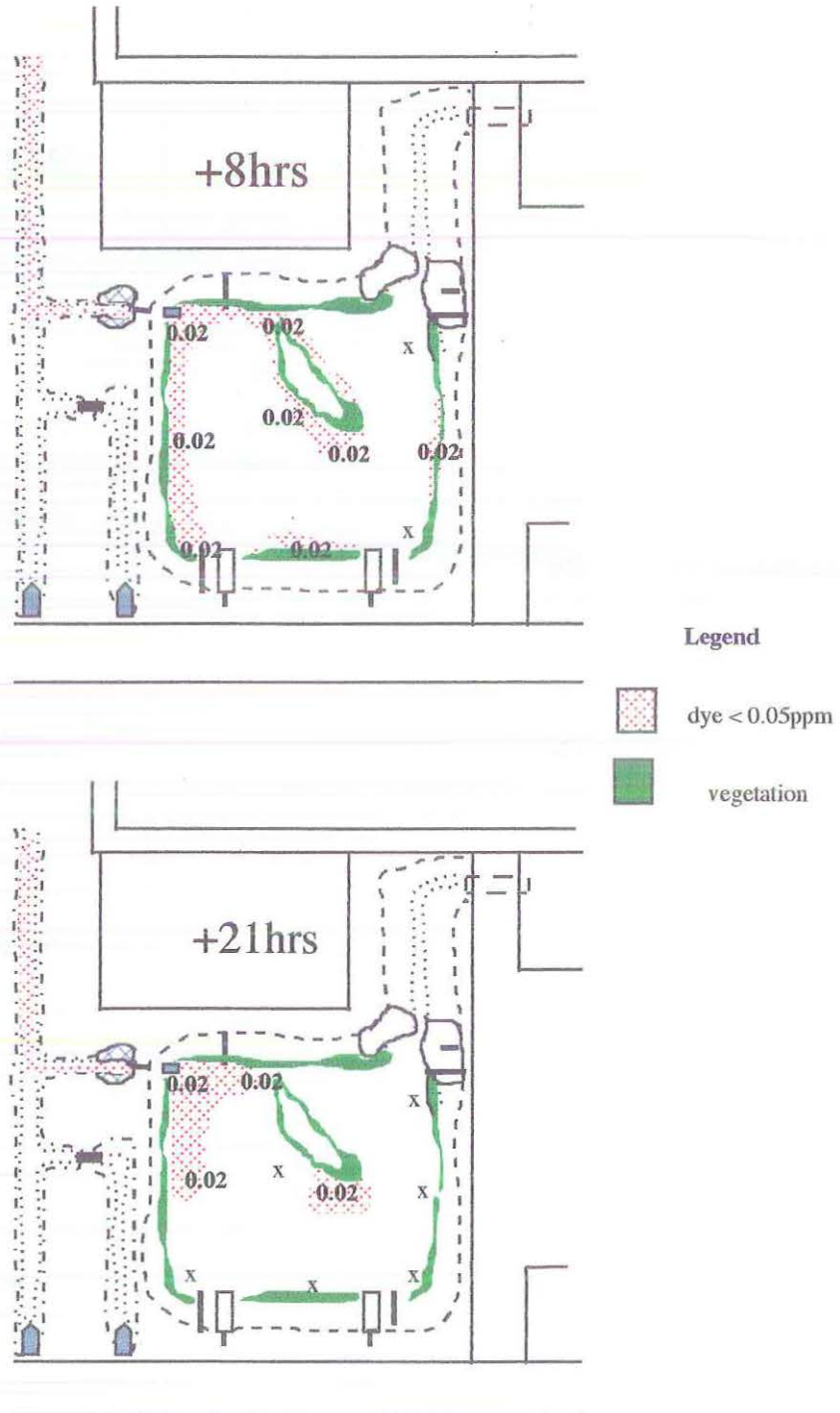


Figure 3.3. (b) Russell Street Rhodamine WT Tracer Dye Trail conducted on the 21.7.95. Sampling intervals at 8 and 21 hours after dye injection. No dye was detected at the 3 hours after injection.



Figure 3.4. (a) Russell Street Rhodamine WT Tracer Dye Trail conducted on 29.7.95. Mixing of labelled water at 1 and 2 hours from time of dye injection. Note that the island was inundated during these sampling periods.



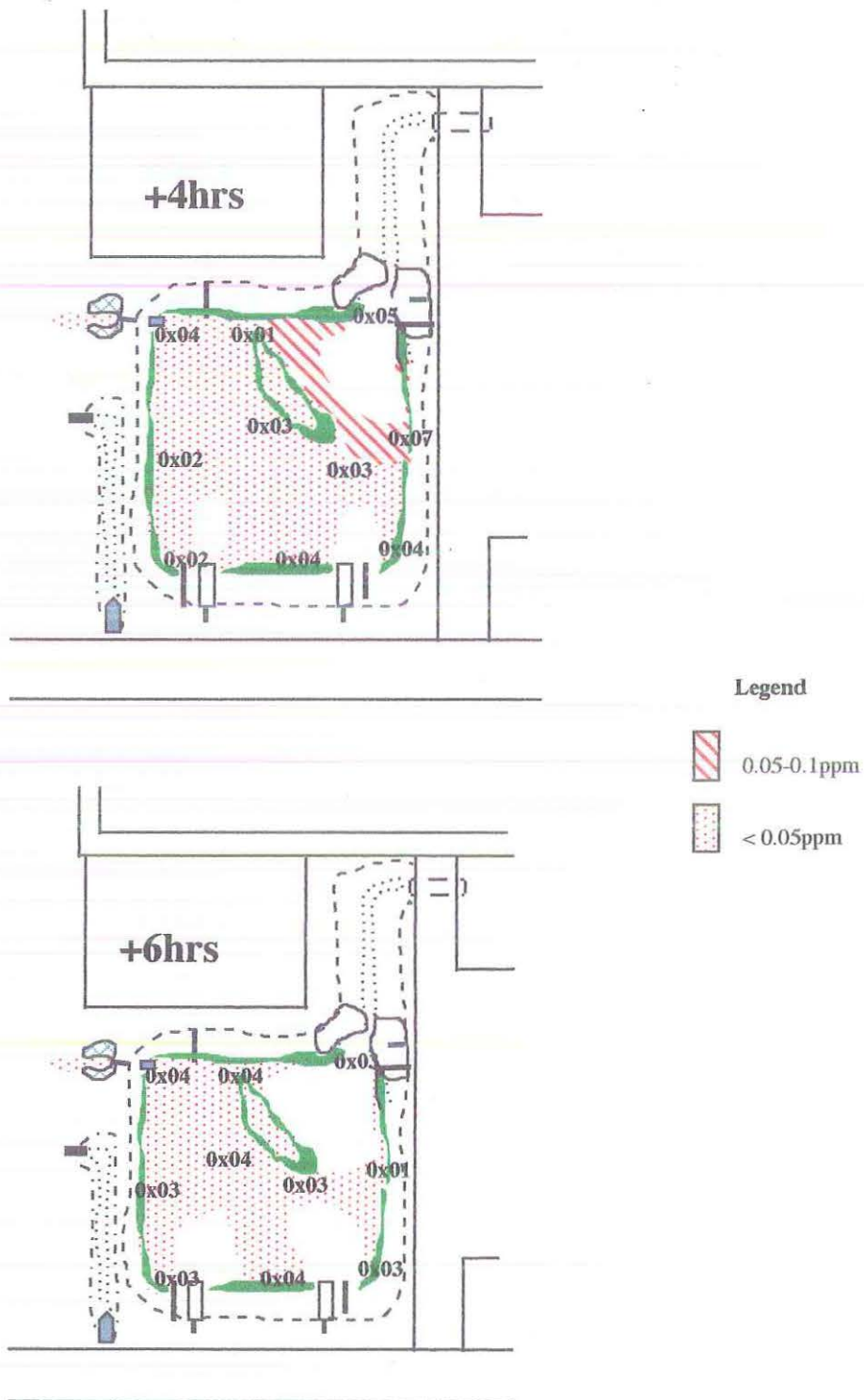


Figure 3.4 (b). Russell Street Rhodamine WT Tracer Dye Trail conducted on 29.7.95. Flow pattern at 4 and 6 hours from time of dye injection.



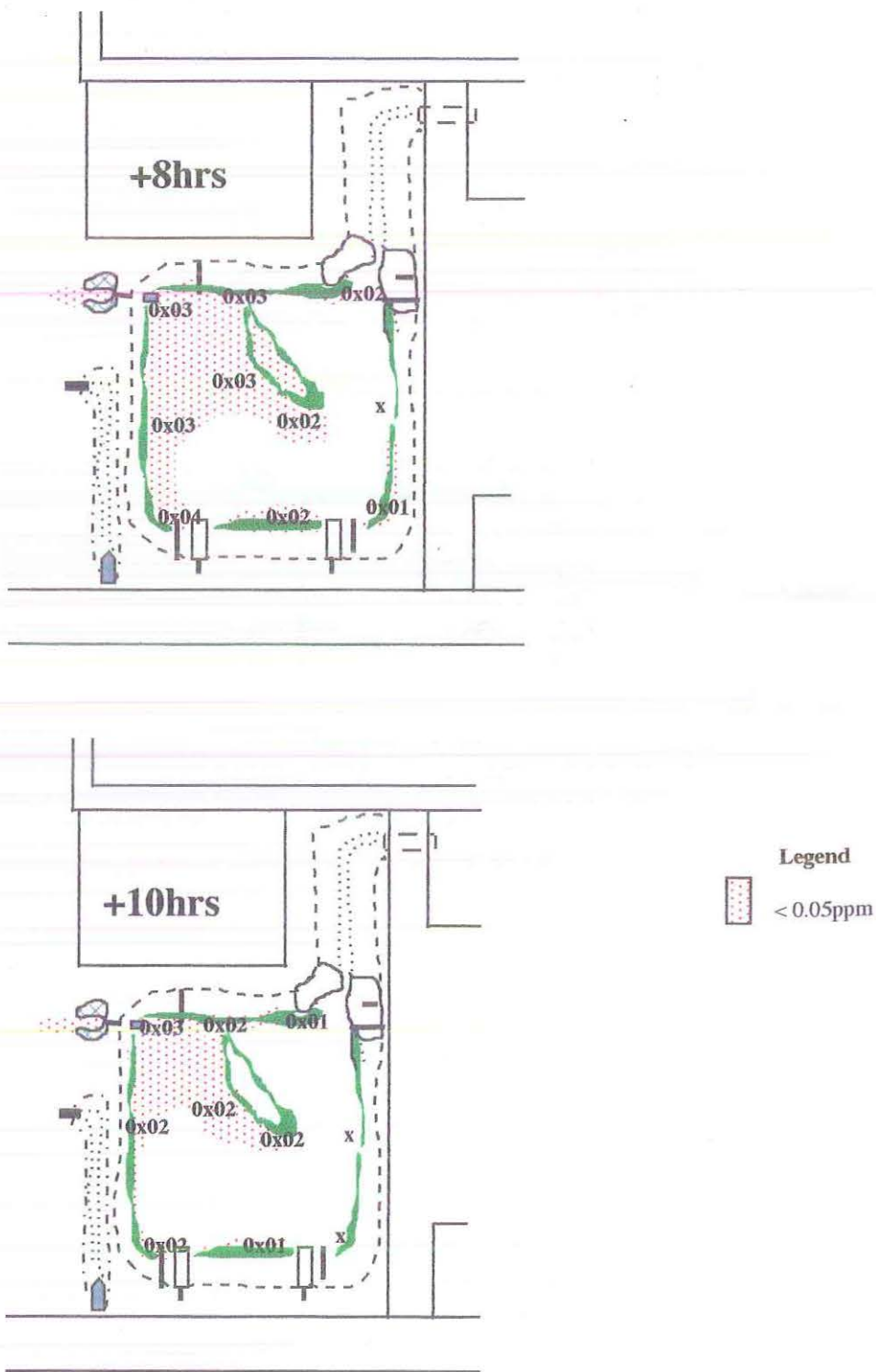


Figure 3.4. (c) Russell Street Rhodamine WT Tracer Dye Trail conducted on 29.7.95. Flow pattern at 8 and 10 hour from time of dye injection.

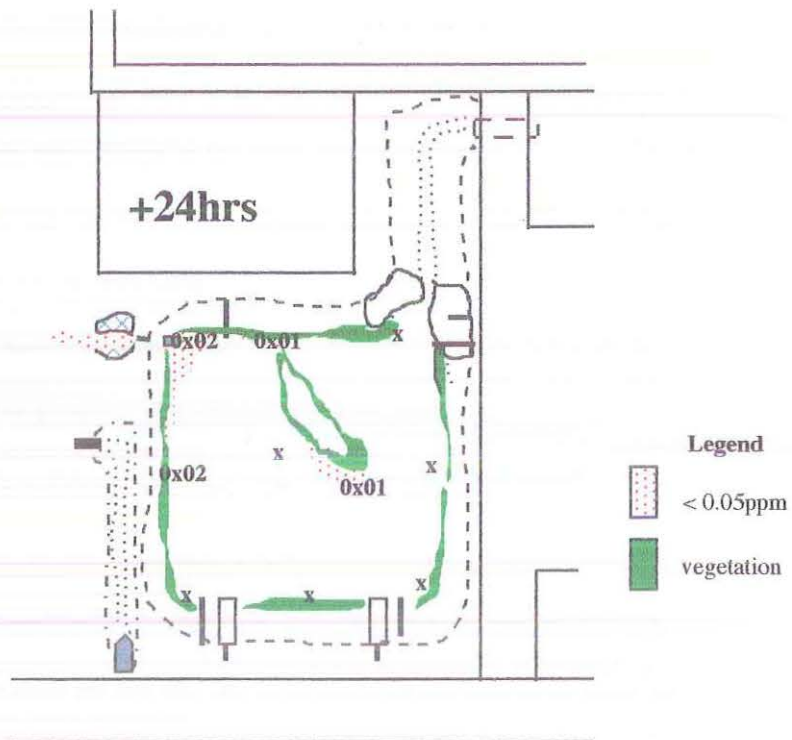


Figure 3.4. (d) Russell Street Rhodamine WT Tracer Dye Trail conducted on 29.7.95. Flow pattern at 24 hours from time of dye injection. No dye was detected 34 hours after injection.

### **Hird Road Flow Regime, Resident Time & Concentration Contours**

The initial flow trial conducted between the 19-24.7.95 at Hird Road revealed an inconsistent flow pattern. Flow between cell 1 and cell 2 for this period indicated a well mixed regime with the discharge concentration peaking at one hour interval and decreasing in concentration over a forty-six hour period (Figure 3.5). Discharge concentration detection at the wetland outlet drain was intermittent, being detected at the 72 and 120 hour sampling intervals. Similar intermittent detection of Rhodamine WT occurred within the wetland at the same intervals (Figure 3.7 a-d). The flow into cell 2 indicated channel flow during the 4.5, 19 and 28 hour sampling periods (Figure 3.7 a & b) but a well mixed and distributed flow during later sampling (Figure 3.7 c-d). The concentration contours plotted for this trial also indicate that there were dead zones in cell 1 (Figure 3.7 a & b) that may contribute to the inconsistent flow pattern. The inconsistent flow pattern is also depicted by the variability in inflow volumes against a steadier outflow during the sampling period (Table 3.4).

The storm event for the initial trial was the same for Russell Street and the inflows were rated between the 10 and 90 percentile of 1994 flow data (Fuller & Deane, 1995). The theoretical residence time exceeded seven days for the trial period however an accurate determination of actual residence during the sampling period was not possible due to the inconsistent nature of the flow. On the concentration detected at the two sampling intervals (Figure 3.5) it was calculated that 25% of the labelled waterbody had been discharged during the trial.

The replicate trial was specifically designed to investigate the flow pattern of the natural wetland cell isolated from the suspected circular flow in cell 1. The rainfall recorded during the second trial totalled 24.4mm which represented a storm event rated at the 70th percentile with monthly return frequency (Evangelisti, 1994). Flow within the natural wetland appeared to be channelled (Figure 3.6) and as such imitated a plug flow regime. Some initial mixing of the labelled water and standing water occurred after which the diluted waterbody moved through the wetland as a plug. The reduced inflow volumes (Table 3.4) meant the labelled waterbody was not pushed across the wetland as in the initial trial (Figure 3.7 a.) but tracked through the southern to central portions (Figure 3.6). The plug flow of the replicate trial enabled an accurate determination of residence time for water in the natural cell of the constructed wetland. Estimating the discharge volume of 270m<sup>3</sup> for the period between Rhodamine WT detection

intervals at the outlet established that 90% of the labelled water had been discharged after twelve hours from the commencement of the trial. This contradicted a theoretical residence time of five days. The effect of the reed beds in retarding flow was apparent in that the only detection of Rhodamine WT at twenty hours was in the densest reed area (Figure 3.6).

Table 3.4. Flow volumes for the Hird Road constructed wetland during the two trial periods. The volumes displayed for the replicate trial between cell 1 & 2 are the sampling period on each date.

Inflow & Outflow Volumes (m <sup>3</sup> )						
Trial 1	19.7.95	20.7.95	21.7.95	22.7.95	23.7.95	24.7.95
Inflow	771	593	165	0	0	734
Outflow	622	1175	1296	967	795	1019
Trial 2	8.8.95	9.8.95	10.8.95			
Inflow	478	138	32			
cell 1 to 2	(471)	(1116)	(508)			
Outflow	414	682	682			

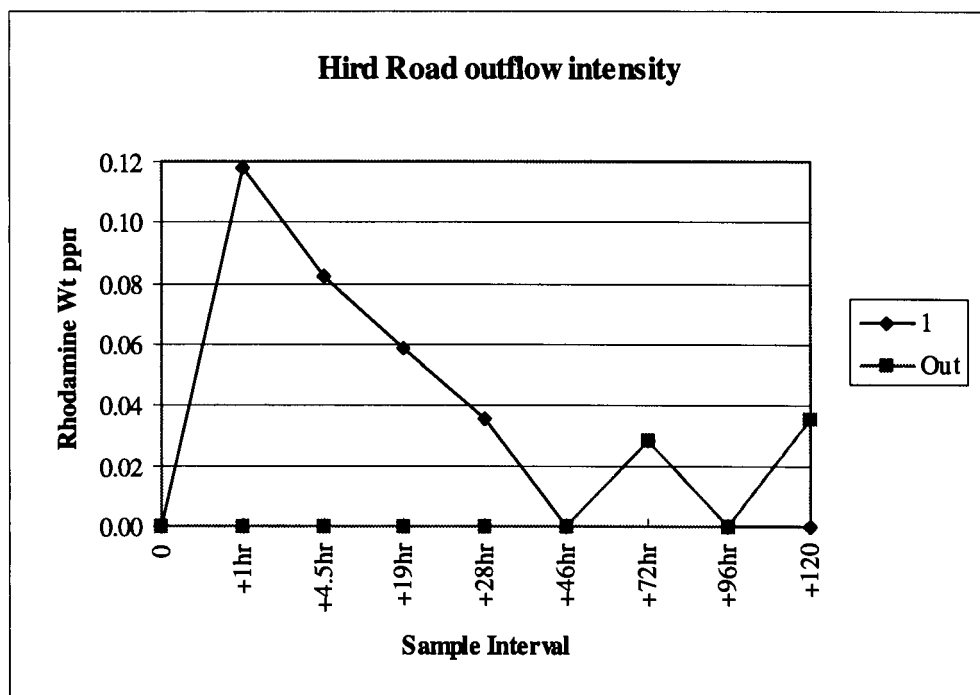


Figure 3.5. Hird Road constructed wetland. Rhodamine WT concentration levels at the ouflow from cell 1 and at the discharge point for the wetland.

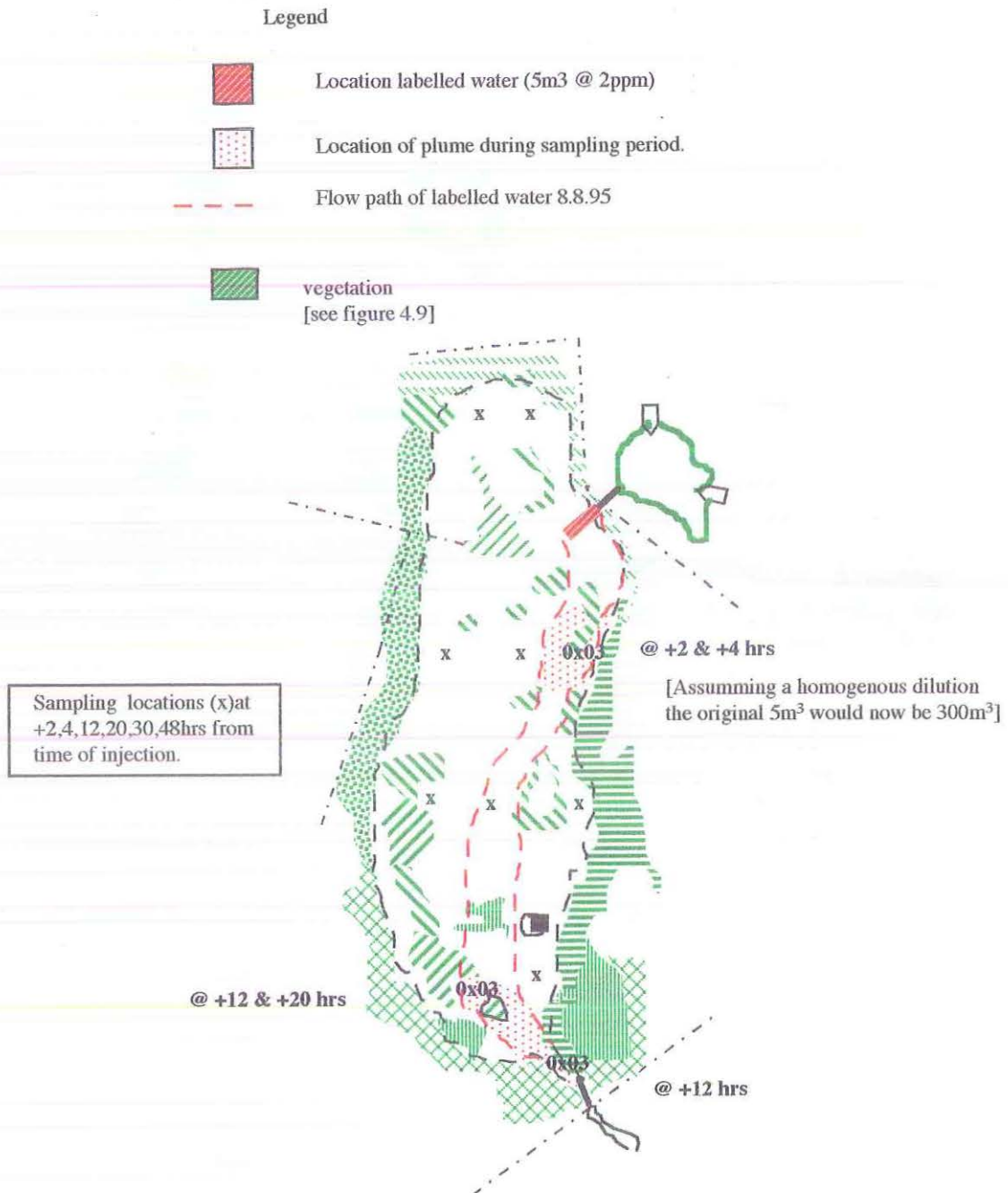


Figure 3.6. Hird Road Buffer Lakes. A 5m<sup>3</sup> column of water in the natural wetland was labelled with Rhodamine WT at 2 ppm and its movement traced through the wetland over a 48 hour period.

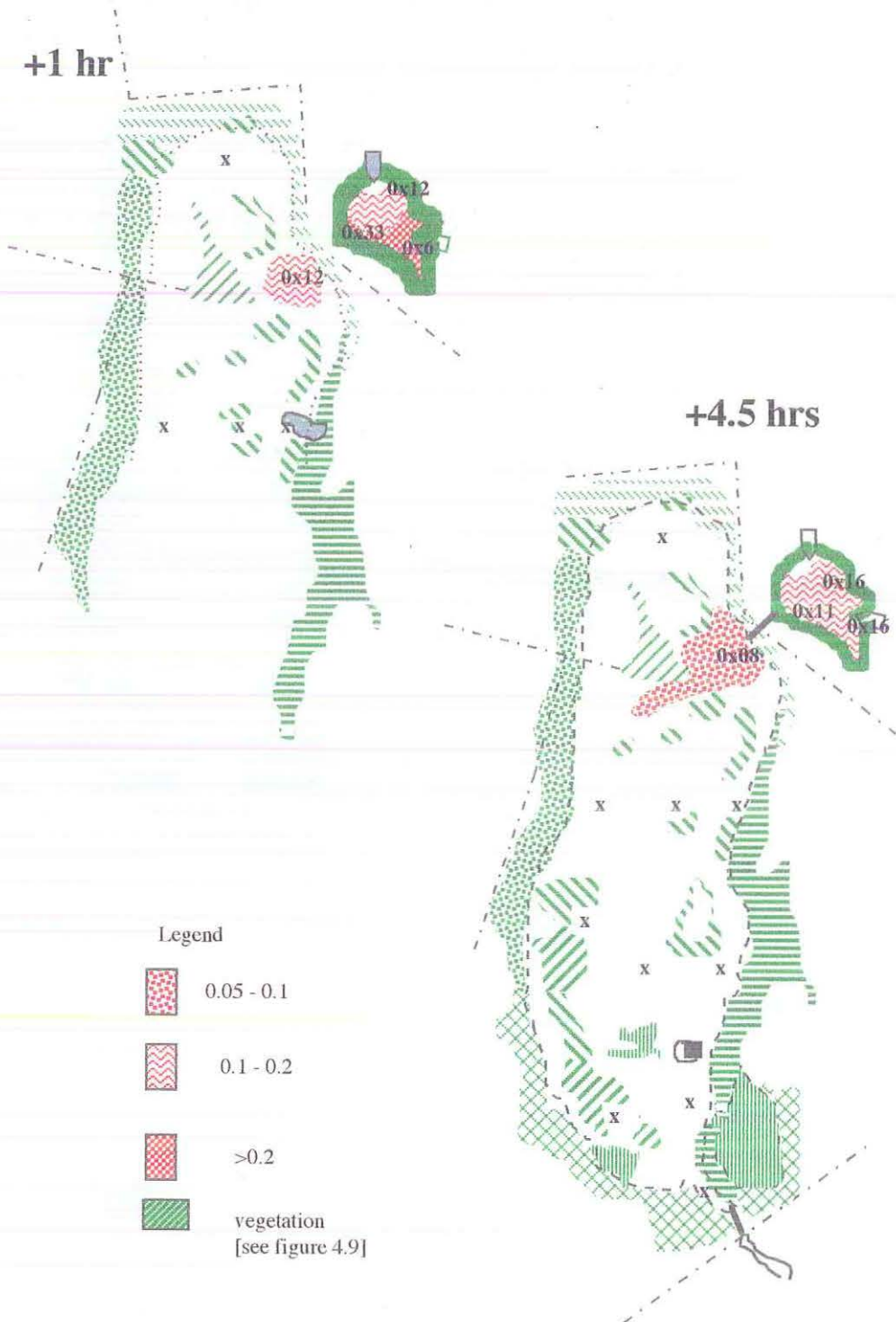


Figure 3.7 (a). Hird Road Buffer Lakes. Labelled water distribution 1 hour and 4.5 hours after dye injection into the inflow at 12pm on the 19.7.95. One cubic metre of inflow was labelled with Rhodamine WT at 300ppm concentration.



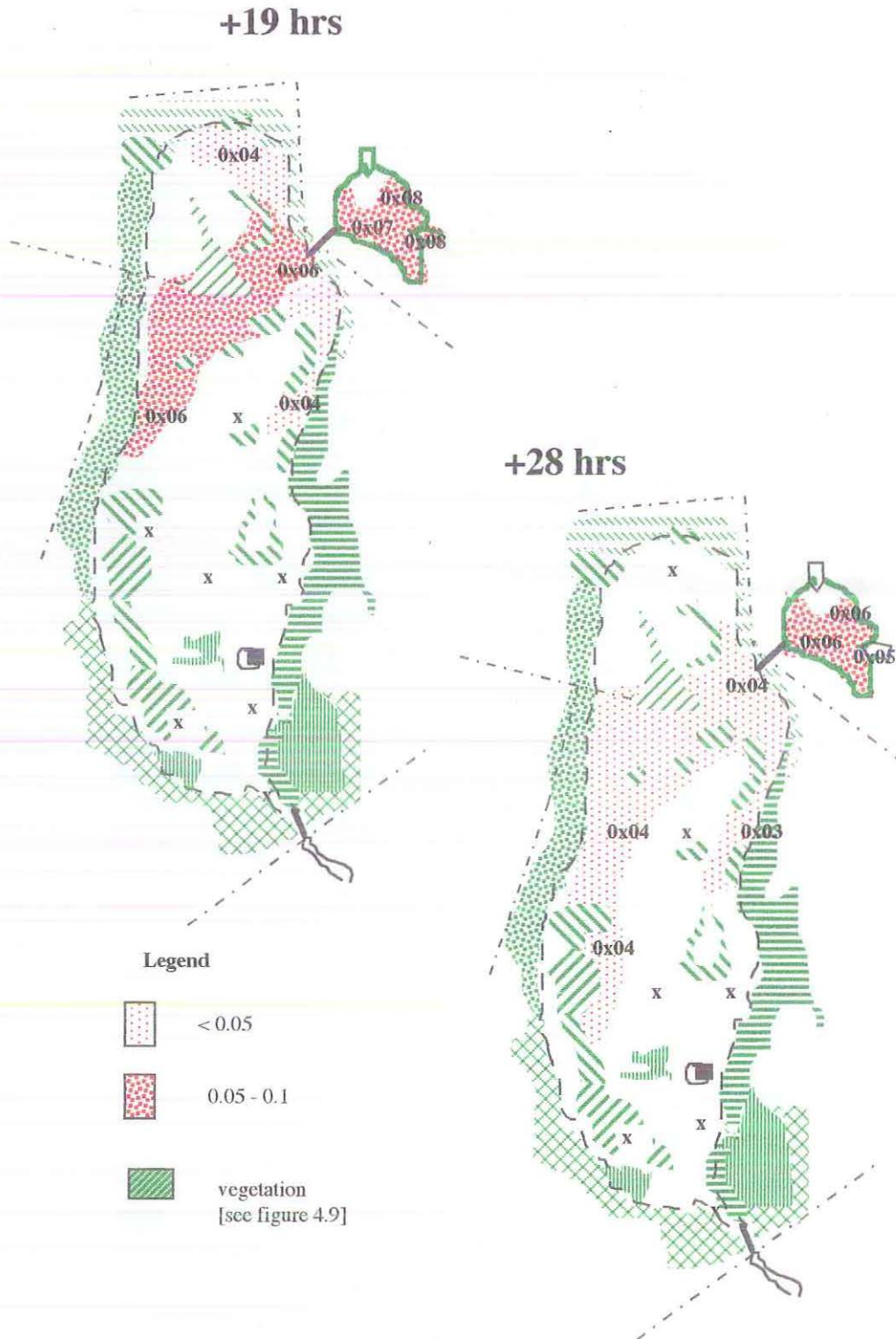


Figure 3.7 (b). Hird Road Buffer Lakes. Labelled water distribution 19 hours and 24 hours after dye injection.

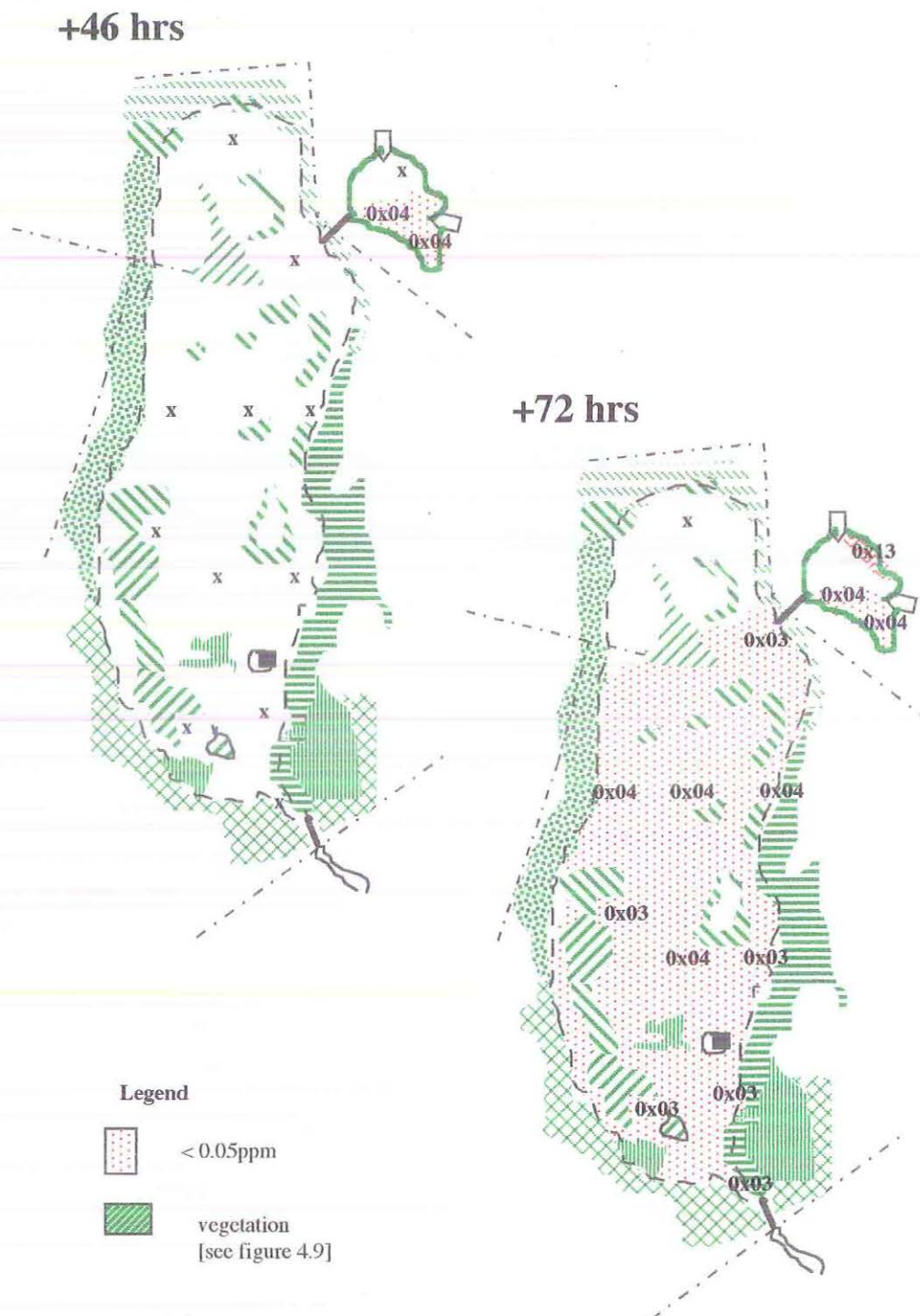


Figure 3.7 (c). Hird Road Buffer Lakes. Labelled water distribution 46 hours and 72 hours after dye injection.



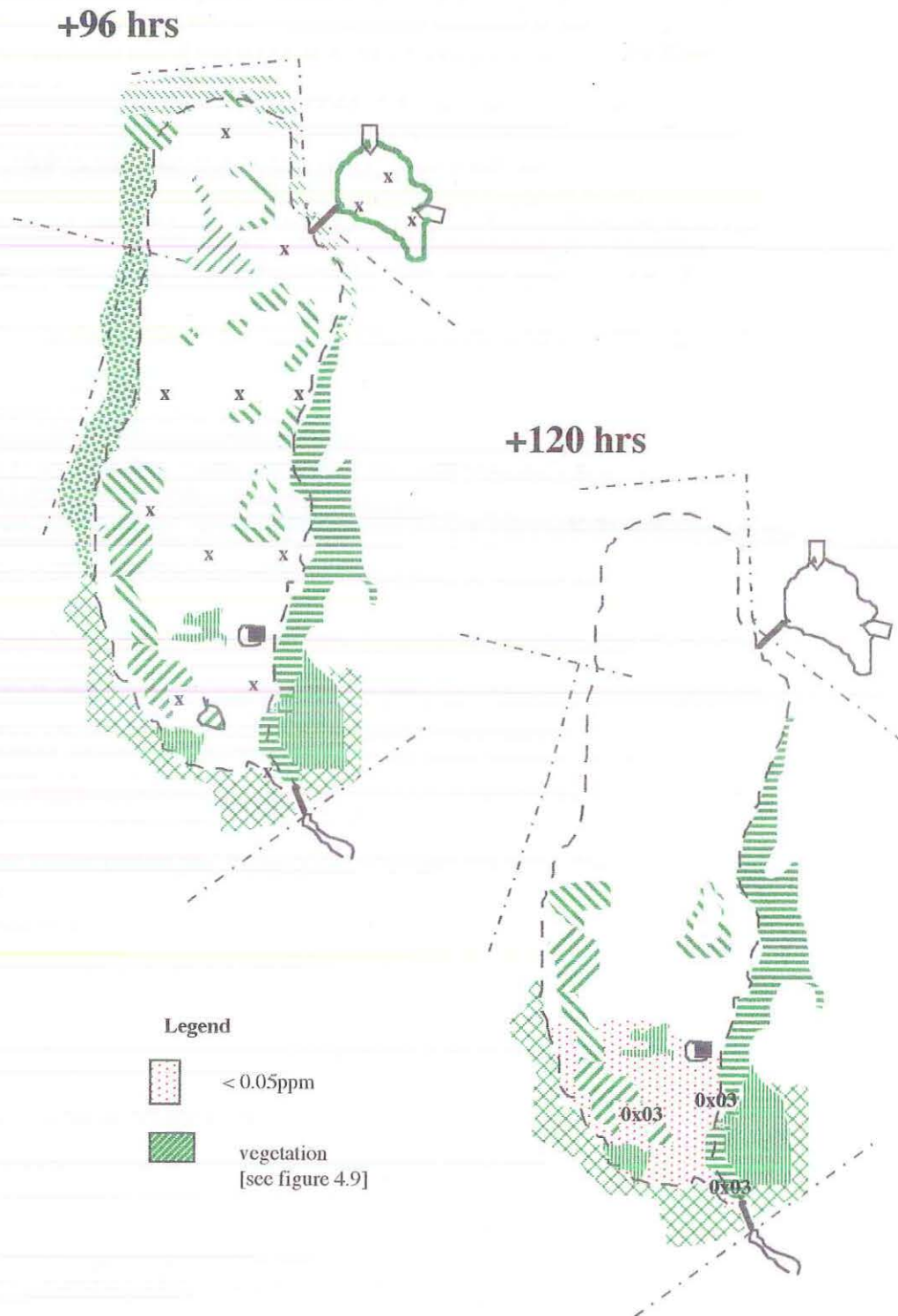


Figure 3.7 (d). Hird Road Buffer Lakes. Labelled water distribution 96 hours and 120 hours after dye injection.

### **Bartram Road Flow Regime, Resident Time & Concentration Contours**

The Rhodamine WT tracer dye trial at Bartram Road indicated a complex flow pattern. The rainfall for the sampling period was the same as for the initial trials at Hird and Russell constructed wetlands. The inflows recorded for the period (Table 3.5) were all less than the tenth percentile of inflows for 1994 winter months (Fuller & Deane, 1995). Total inflow for the period did not exceed the storage capacity of the system ( $50000\text{m}^3$ ) and on a theoretical basis the residence time of the inflow should exceed twenty days. The accumulative inflow for the 1995 winter period exceeded the storage capacity for the first time at 5pm on 20.7.95. This was reflected in the sudden increase in outflow volume on the 20 & 21.7.95 (Table 3.5).

The complex flow regime varies from one approximating a plug in cell 1 to completely mixed flow in cell 5 (Figure 3.8). This was apparent with the dye concentration decreasing at each cell outlet through the wetland. The degree of mixing ranged from an estimated 600 times dilution in cell 1, followed by a 3x, 1.5x and 2.3x in subsequent cells. Channel flow was also apparent in concentration contours plotted in all cells except the last cell (Figure 3.9 a-h). The channel flow coincided with areas affected by culvert connections between cells and areas where channels have been created through vegetated areas. The initial dispersal of the labelled waterbody was influenced by strong south-west winds which pushed the plume against the fringe of cell 1 (Figure 3.9 a-b). The surface current imposed by the wind appeared to create dead zones within the first cell that resulted in inconsistent mixing and discharge of the labelled water from this cell.

At the conclusion of the study an estimated 59% of the labelled water had been discharged in the last three days of the sampling period (Table 3.5). The actual residence time was extrapolated assuming concentration on the day after the conclusion of the trial. The assumed concentration of 0.06ppm for day 6 was based on the lowest concentration detected on day 5 (Figure 3.9j). Applying this value to the known outflow volume for the 25.7.95 (day 6), 100% of the labelled water would have been discharged by the end of that day. The actual residence time for the labelled water body was estimated at six days. Short-circuiting resulting from the channel flow appears to have reduced the theoretical residence time by a factor of four.

The influence of vegetation on flow in the cell 4 is negated by the channelling of flow through this, the largest cell of the constructed wetland (Figure 3.9 g-j).

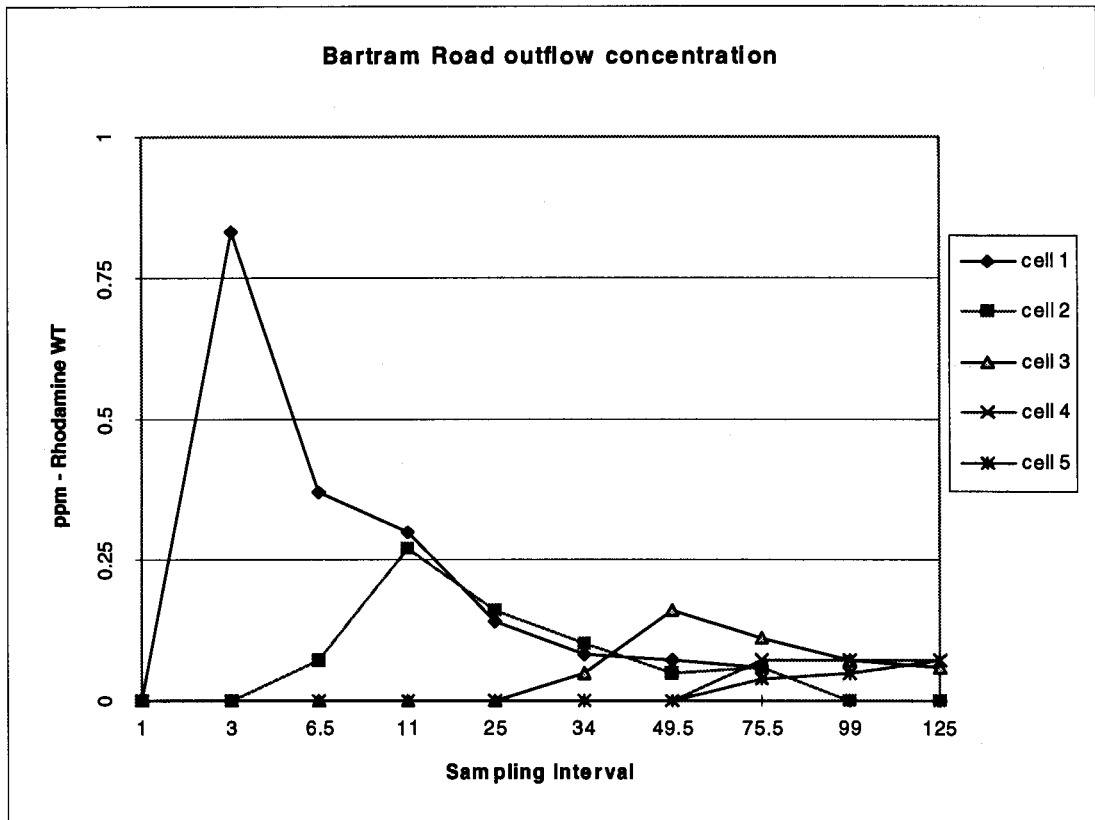


Figure 3.8. Bartram Road constructed wetland. Outflow dye concentrations for each cell within the wetland at sampling intervals.

Table 3.5. Bartram Road constructed wetland. Inflow & Outflow volumes and labelled water discharge during dye trial commenced 19.7.95. Dye was first recorded in outflow samples on the 22.7.95, three days after the dye injection. % labelled waterbody discharge shown is accumulative. The concentration on the 25.7.95 is estimated from the concentration contours in figure 3.9(j).

Date	19.7.95	20.7.95	21.7.95	22.7.95	23.7.95	24.7.95	25.7.95
Inflow (m <sup>3</sup> )	1496	2008	1762	1510	1431	2108	2785
Outflow Volume (m <sup>3</sup> )	593	1138	2058	1602	1436	2262	3515
Dye concentration (ppm)	0	0	0	0.04	0.05	0.07	(0.06)
% labelled water discharged				13	27	59	101

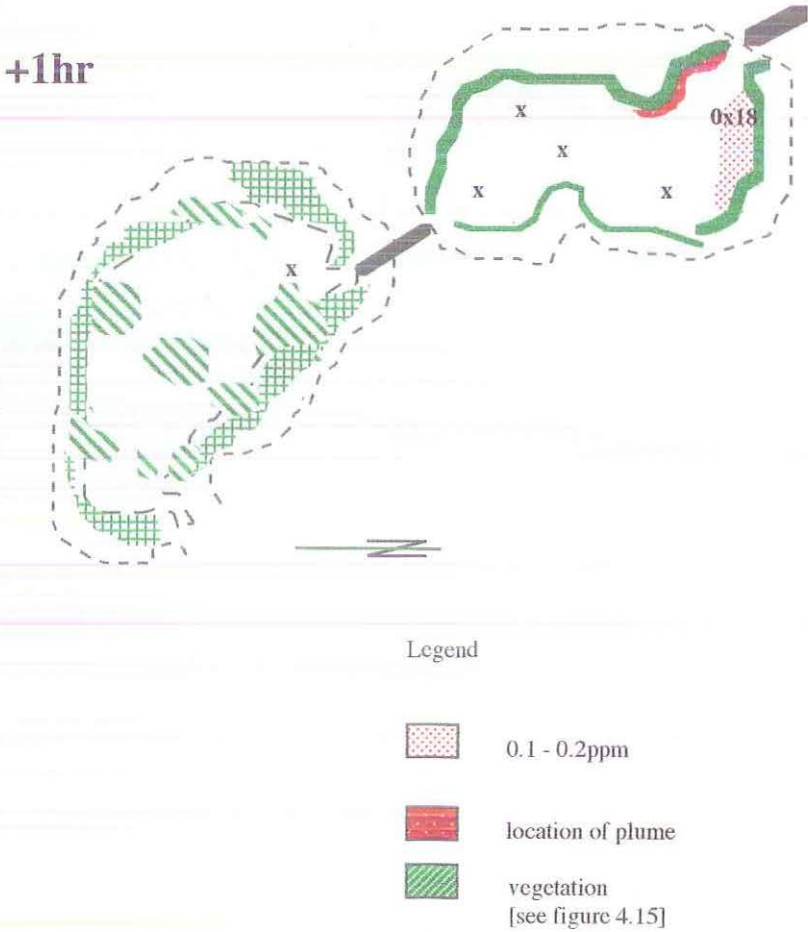


Figure 3.9 (a). Bartram Road constructed wetland Rhodamine WT concentrations 1hr. after dye injection. The trail commenced at 7:00am on the 19.7.95 and was concluded at 12:00pm on the 24.7.95. The labelled water was visible in the forebay of the first cell (red shading). Strong SW-winds appeared to affect the dispersal of the labelled water. "x" designates water sample locations where no Rhodamine WT was detected.

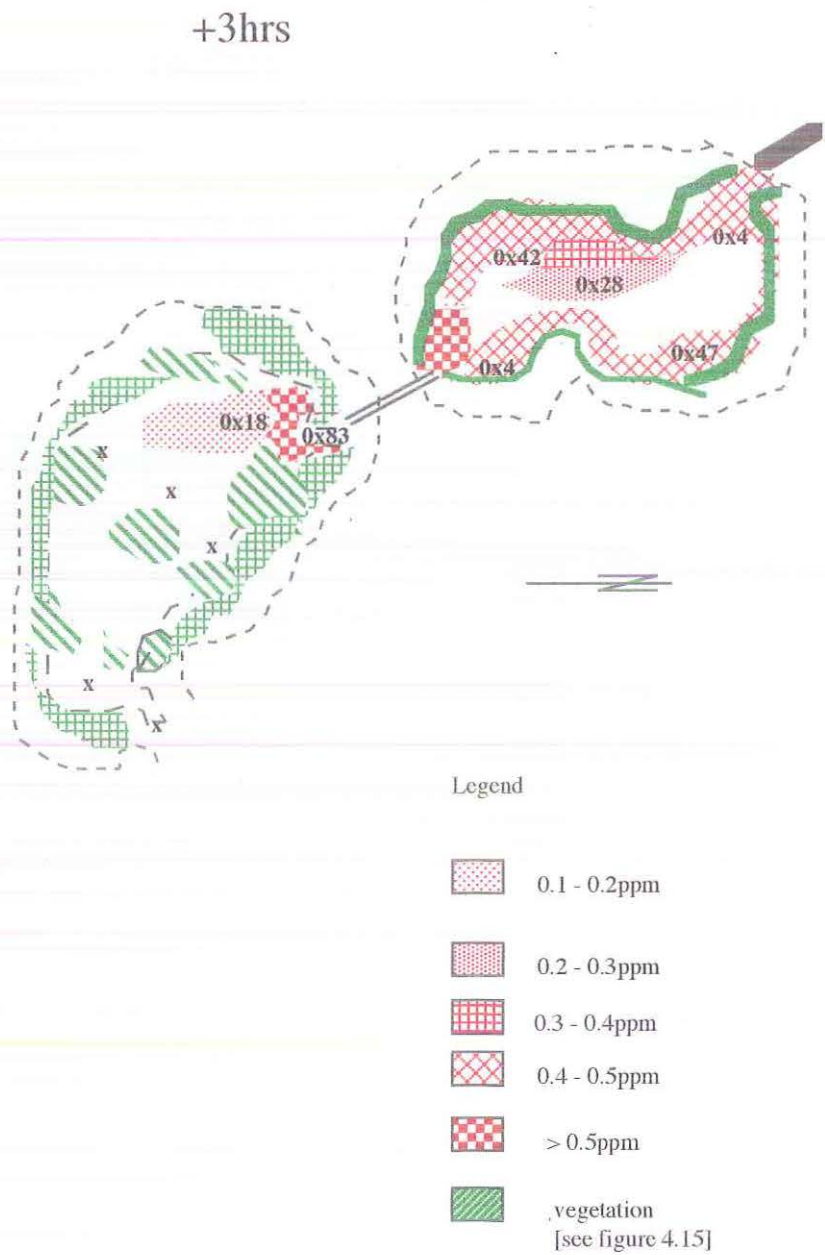


Figure 3.9 (b). Bartram Road constructed wetland Rhodamine WT concentrations 3hrs. after dye injection.

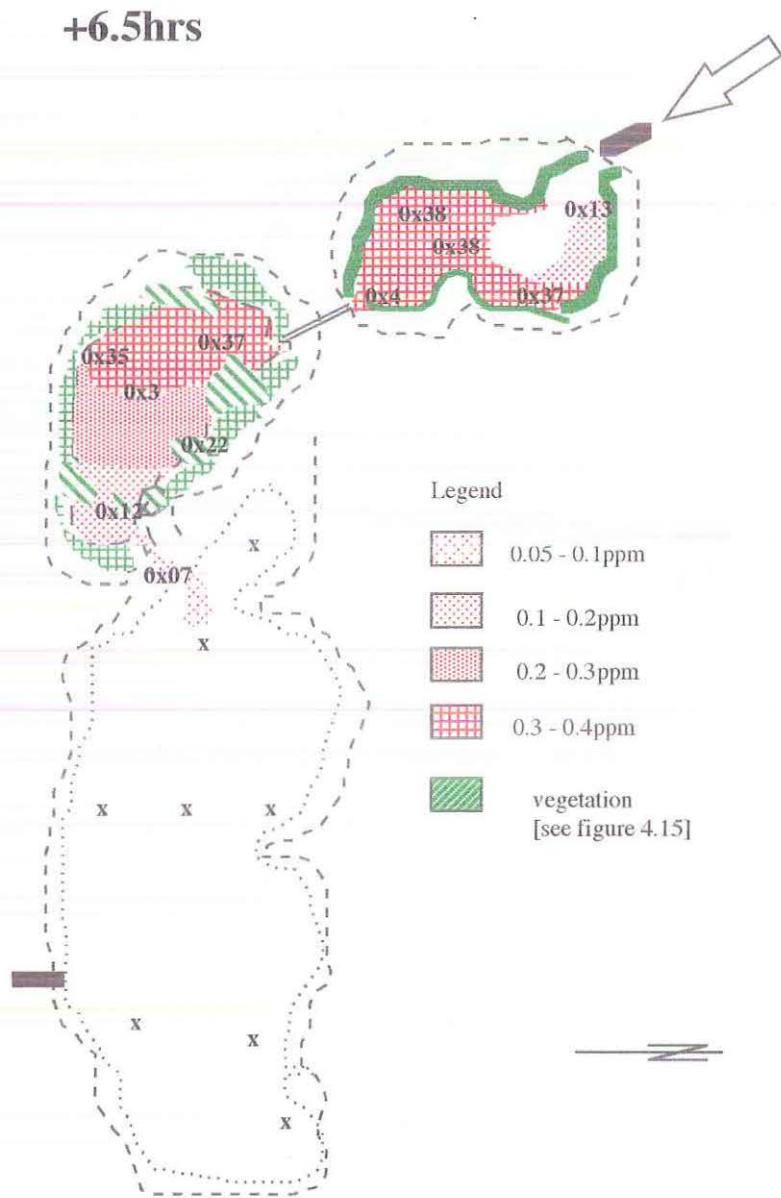


Figure 3.9 (c). Bartram Road constructed wetland Rhodamine WT concentrations 3hrs. after dye injection.

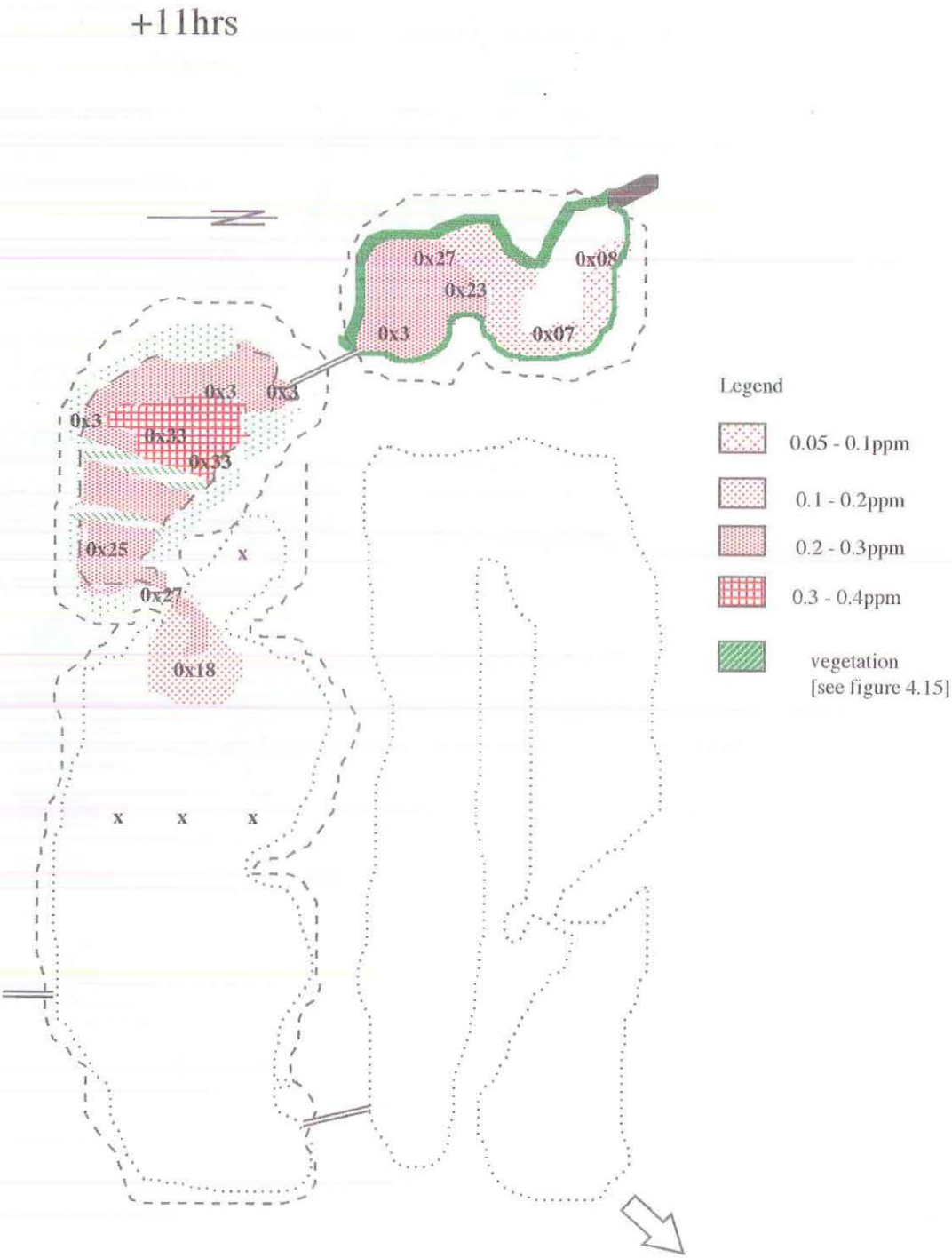


Figure 3.9 (d). Bartram Road constructed wetland Rhodamine WT concentrations 11hrs. after dye injection.



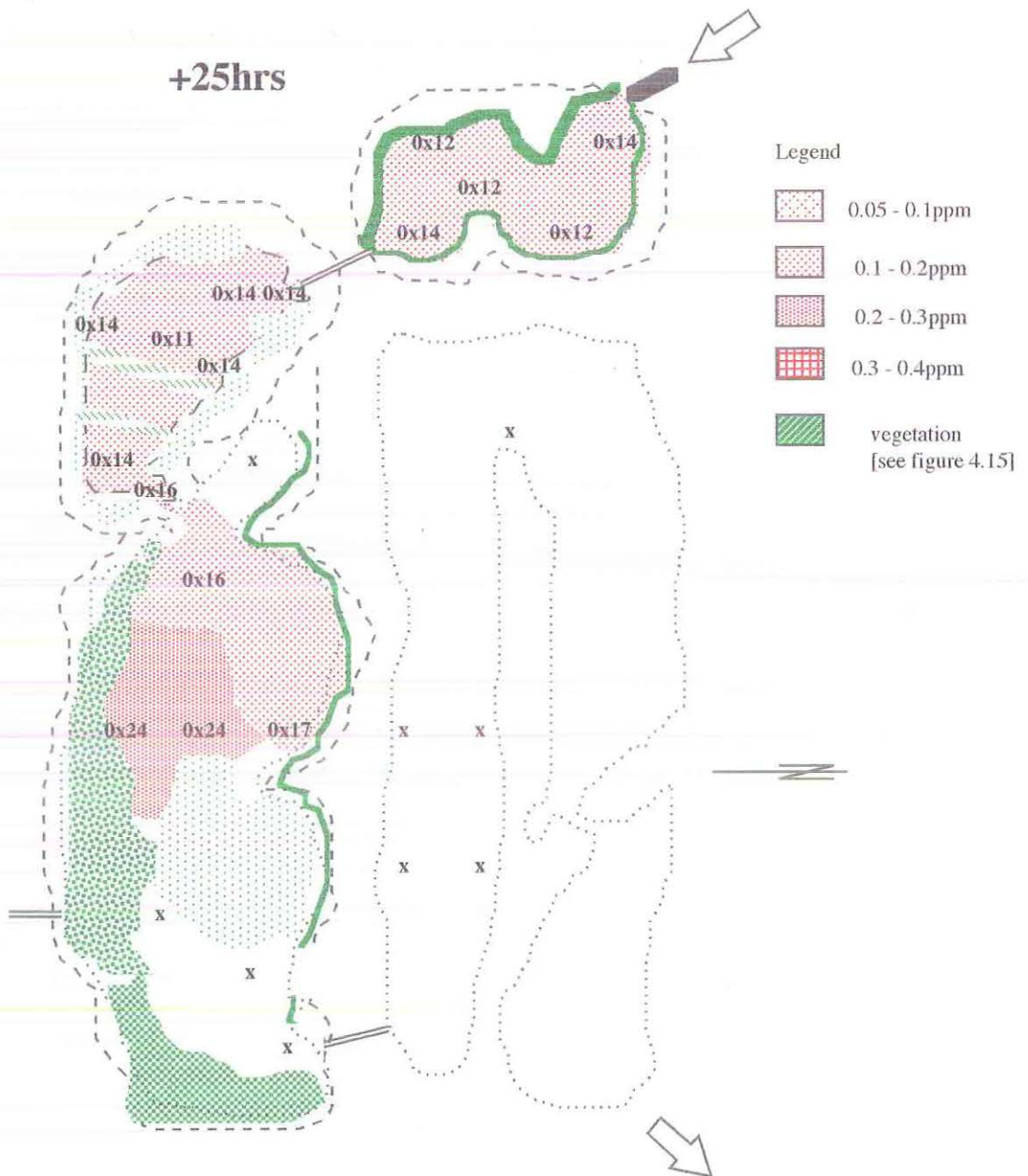


Figure 3.9 (e). Bartram Road constructed wetland Rhodamine WT concentrations 25hrs. after dye injection.



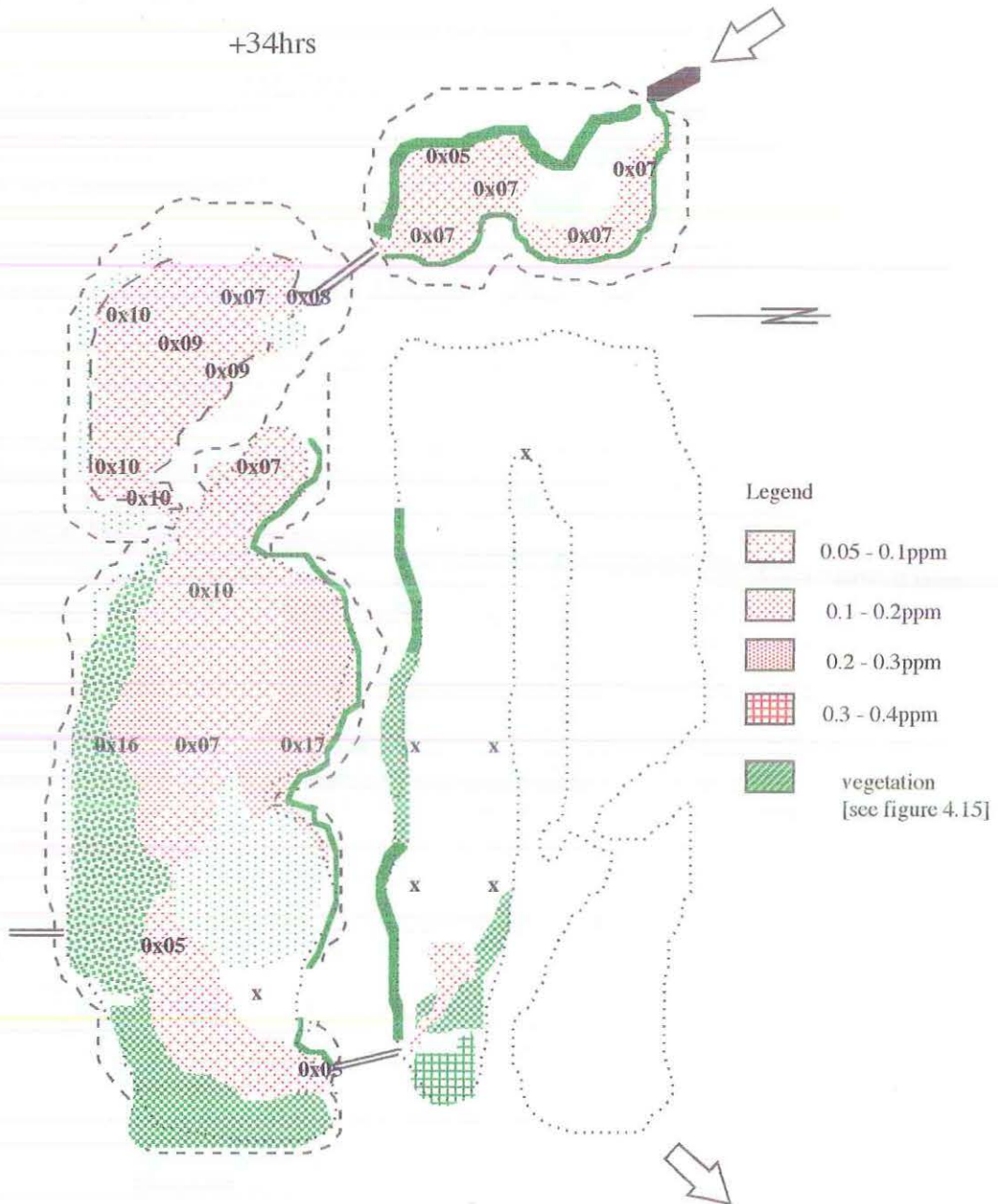


Figure 3.9(I). Bartram Road constructed wetland Rhodamine WT concentrations 33hrs. after dye injection.

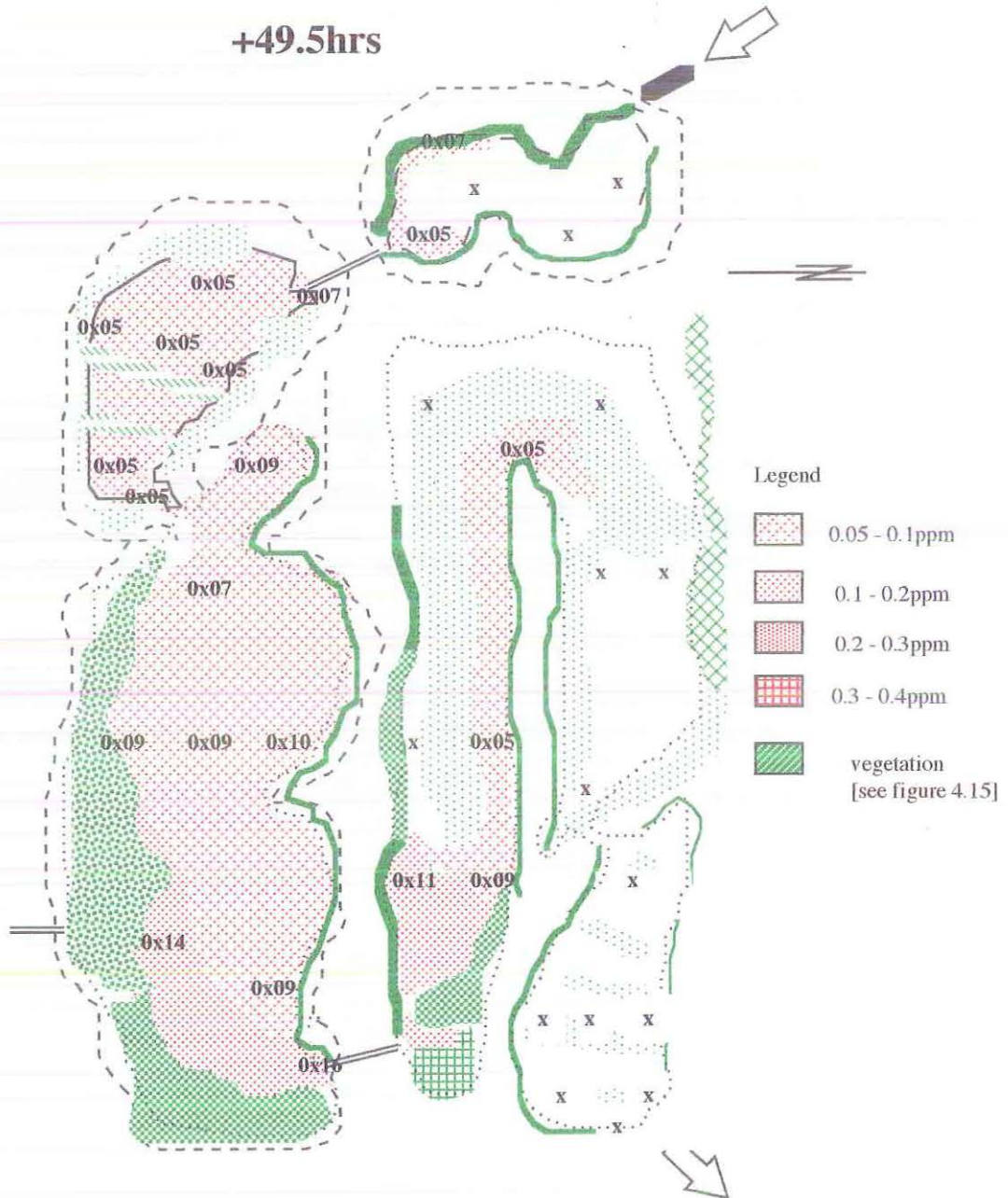
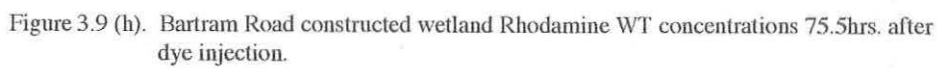
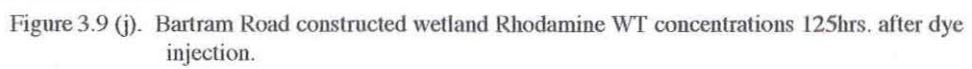


Figure 3.9 (g). Bartram Road constructed wetland Rhodamine WT concentrations 49.5hrs. after dye injection.









## ***Discussion***

The inflow volumes and the rainfall events for the flow trail periods were not extra-ordinary. The storm events rated within the 90th percentile of storms for the Perth area which is the recommended coverage of storms to establish design parameters (chapter 2). It was therefore expected that the theoretical residence times would be met under the study conditions. The residence time at Russell Street did match the theoretical residence time. However storage volume of this constructed wetland is drastically underestimated to meet the design residence time of five days (chapter 2). The actual residence times at Bartram and Hird differed to the theoretical times by a reduction factor of four. This reduction in actual residence times has the potential to significantly lower CRE performance by not allowing for the temporal requirement of wetland removal functions (Livingston, 1994). The poor CRE established for all the study sites during August 1995 (Chapter 4) is most likely directly related to the reduction in residence times.

Whilst supporting the findings of Kadlec et al.(1993) that plug flow is not reproduced in field conditions the results of this study indicate that various design elements can be adapted to achieve approximate plug flow. This is done by removing those elements that encourage channelling and thus cause short-circuiting of the design flow path. Five elements identified by this study as a cause of short-circuiting are:

- use of culverts or trenches as connections to internal cells (Bartram, Hird),
- the lack of diffuser structures at inlets (Bartram, Hird, Russell),
- poor positioning of cell connections (Bartram, Hird),
- the change in flow path at maximum storage capacity or intense inflow (Russell, Hird),
- the fetch effect in open water areas (Bartram, Hird) and
- lack of dense homogenous vegetation areas (Bartram, Hird, Russell).

All of the elements listed above are contrary to optimal design discussed in chapter 2. The simple principle that water will follow the path of least resistance appears to have been overlooked in the design and construction of the study sites. This is particularly relevant to vegetation areas. Design must ensure

that channels are not inadvertently created through non-homogenous planting. Conversely dense vegetation used at inlets will reduce channelling created by culvert inlets. Similarly, the fetch of open water areas can be minimised by the interspersal of vegetation. The vegetation effect of retarding flow was apparent at all the wetlands sites (Guntenspergen et al., 1989). As noted in the Bartram results, the channel flow created by inappropriate construction techniques in cell 4 has meant that the influence of this large and otherwise densely vegetated cell is negated. Similarly the location of the connection drains between cells at Bartram creates significant dead zones and actually reduces the effective surface area by an estimated 1000m<sup>2</sup> (Figure 4.15). The location of the cell connection at Hird reduces the effective flow path by an estimated thirty per cent.

Given that 'as constructed' assessments were not performed on the sites (chapter 4) it is unlikely that managers would be aware that short-circuiting of the flow path is occurring. The major finding of the Rhodamine WT tracer dye trials was the real need to perform such studies as an integral part of constructed wetland performance evaluation and management. The flow pattern during the replicate trial at Hird Road indicated the importance of within wetland sampling. Without that internal sampling that produced the concentration contours the result of charting outflow concentrations would have indicated a plug flow regime and would not have shown the channel flow that caused short-circuiting of the flow path.

Concentration contours were useful in highlighting significant shortfalls in the design and construction of the study site projects and supported the findings of Livingston (1994), that channel flow is to be avoided. The replicate studies conducted at Russell and Hird suggest that flow studies need to be repeated not only for different rainfall events but also within specific cells of the wetland. Such studies would have to be repeated at regular intervals and could be aligned with the comprehensive assessment requirements discussed in chapter 2. Routine flow studies are necessary to assess whether the evolution of the constructed wetland has not inadvertently created channels that will reduce the effective performance of the wetland.

## **Chapter 4**

# **Nutrient Retention Studies**

## ***Determination of Contaminant Removal Efficiency and Nutrient Storage of Constructed Wetland Sites.***

### ***Introduction***

The purpose of constructed wetlands as a treatment for urban stormwater runoff is to remove pollutants from inflow water and thus improve the water quality of discharge to receiving environments. Chapter 2 examined the theoretical elements required to achieve this while chapter 3 examined the actual flow patterns associated with three constructed wetlands. This chapter determines the Contaminant Removal Efficiency (CRE) of those same constructed wetlands for a designated three day period. CRE determination was for the selected pollutants of phosphorus, nitrogen and lead. The nutrient suite (phosphorus in particular) is the focus of performance evaluation for the management of the study sites. The detection of lead at Russell Street (Klemm & Switzer, 1994) and at Hird Road (Fuller & Deane, 1995) selected this element as a representative of other urban pollutants carried by stormwater.

The CRE of the respective wetlands was then related to the individual structure and the theoretical concepts discussed in chapter 2. In particular the determination of CRE of a three day period provided a comparison with the findings of Livingston (1994) and Evangelisti (1994). These findings discussed in chapter 2 (Project Design Elements) cite a minimum residence time of three days to achieve effective particulate pollutant removal. Varying methods of reporting CRE are presented to investigate differences these produce in assessing wetland performance. The CRE of each wetland was compared to evaluate the effectiveness of their individual design. Their performance was also compared to CRE discussed in the literature.

In addition to CRE determination, wetland assimilation of contaminants from inflow water is examined by sampling the major nutrient stores within wetlands. Again the analysis of nutrient stores in the soil,



water and plant stores of each of the wetlands is compared and related to their individual design elements. The comparison of wetland stores is also related to the design elements discussed in Chapter 2. In particular the storage capacity of varying substrate type is compared to findings by Marble (1992), Faulkner & Richardson (1989) and Hammer (1992). First, the substrate is the major store with a wetland system. Second, that the type of substrate is important to the retention capacity and to the type of nutrient retained. Similarly, vegetation stores are compared to establish the relevance of species or composition complexity to the retention capacity of this store. Studies by Chambers & McComb (1992) on local wetland species showed the period of inundation negatively affected the plant's ability to uptake nutrients and reduced their capacity to store nutrients. Guntenspergen et al. (1989) found that a complex vegetation assemblage contributed to the wetland's ability to adjust to a range of perturbances.

Preliminary works on this study revealed that there were insufficient data on the physical properties of the constructed wetlands to allow calculation of nutrient store. This necessitated mapping of the constructed wetlands to establish surface areas, vegetation areas and storage volumes. The implications to management agencies of not having up-to-date plans of constructed wetlands are discussed later in this chapter.

## **Methods**

At each of the constructed wetland sites, three major assessments were undertaken: site mapping, nutrient storage and CRE.

The strategy for the CRE determination and nutrient store analysis is based on the routine and comprehensive assessments discussed in chapter 2. Quality control for the study followed guidelines set out in Green (1979), Hairston (1991) and Kieth (1991). The contaminant suite analysis for water samples of Total Phosphorus (TP), Total Kjeldahl Nitrogen (TKN), Ortho-phosphate (FRP), Ammonia ( $\text{NH}_3$ ) and Nitrate + Nitrite ( $\text{NO}_2 + \text{NO}_3$ ) was designed to be compatible with existing monitoring data at Bartram Road, Hird Road and Russell Street (Dean et al., 1995; Fuller et al., 1995; Tan, 1991 and W G Martinick & Associates, 1994). The soil and plant stores were analysed for TP and TKN.

The study period of three days was selected as meeting the minimum residence time required to achieve effective contaminant removal of particulate matter (chapter 2). It was intended that the CRE study be

conducted during intense rainfall events to examine the effect of extreme events on design parameters. However the forecast storms did not eventuate and the studies were conducted over light rainfall events.

Bartram and Hird Road constructed wetland systems were sampled from 12:00pm on 18.8.95 to 12:00pm on 21.8.95 and Russell Street from the 12:00pm on 28.8.95 to 12:00pm on 31.8.95.

### **Site Mapping**

Standard baseline and offset survey techniques were used to map wetland basin and vegetation areas. The sites were plotted on standard metric grid paper and the areas determined using grid square analysis. Wetland plant species identification used keys from Powell (1990), Marchant et al., (1987), Sainty & Jacobs (1994 & 1981), Paterson (undated) and Bennet (1988).

Volumes of Hird and Russell wetlands were determined from spot depths taken throughout the wetlands. Spot depths at Bartram Road were used to verify design volumes obtained from WAWA (1994), plan No. CT90-1-1\_6. Bartram Road constructed wetland was mapped on the 4th & 5th June 1995, Hird Road on the 10.6.95 and Russell Street on the 11.6.95.

Site anecdotal history at Hird Road was supplied by Mr. Sruzynski, Mrs Hansson and lease holders adjacent to the wetland. Similar anecdotal history for the Bartram Road constructed wetland was volunteered by the current adjacent land owners.

### **Nutrient Store Determination**

The three major storage compartments, soil, plant and water were sampled to determine storage of nutrients. The soil, water and plant stores were sampled at 5 randomly selected sub-sites in each cell in each wetland. These 5 sub-samples were then bulked to provide a single sample for each cell. This procedure was repeated to provide duplicate bulked samples for each cell. A variation on this sampling procedure for plant sampling is explained in detail in the sampling regime section. Field storage of samples involved placing them in an esky where they were chilled at approximately 4°C before transport to laboratory freezers.

The plant biomass and tissue samples were confined to inundated areas to allow a direct comparison of storage compartment loads. Woody species such as the *Melaleuca* were not sampled.

The nutrient store sampling was conducted between CRE sampling. A total set of samples for one replicate was taken before independently repeating the sampling regime for the duplicate set. To avoid contamination of water column samples by substrate disturbance during soil or plant sampling the water column was routinely sampled first.

### ***Sampling Regime***

#### **Soils**

The sediment samples were extracted using a 50mm Oogee Sand Pounder corer (Wildco Instruments, USA). This corer is equipped with a shut-off valve that enables underwater cores to be removed intact. Five cores were taken each to approximately 200mm in depth, and the perspex liner removed, the core and the top 50mm was removed. Five 50mm sub-samples were bulked for each cell, labelled and stored for transport. To avoid cross-contamination all equipment was thoroughly cleaned between sampling of cells.

#### **Plant**

Plant samples for biomass determination and nutrient storage were taken separately. Biomass sampling involved removing all plant material within a 0.09m<sup>2</sup> quadrat to a depth of 50mm. Each vegetation assemblage within each wetland was sampled from five randomly located quadrats. The samples were thoroughly rinsed to remove any substrate material. Due to the bulky nature of the biomass samples they were stored and processed separately.

The constructed wetland biomass was determined by drying biomass samples to constant dry weight. A Memmert Drying Oven was set at 85°C for this analysis. Results from the five quadrat samples for each assemblage were averaged and converted to a kg/m<sup>2</sup> figure. The samples typically required 48 hours to achieve constant dry weight. A total of thirty-five samples were processed.

Samples for nutrient analysis of plant tissue were taken from each vegetation assemblage within each cell of the wetland. This typically involved samples from the fringing assemblage and from the *Baumea* assemblage. Small sections of plant tissue (approximately 25mm in length) were taken from the tips and the stems as well as the rhizome and roots where these were present within 50mm of the substrate surface. Five plants from each assemblage were sub-sampled in this way then bulked to give one sample for each assemblage within each cell of each wetland.

### **Water Column**

Each cell was sub-sampled in 5 locations using a meter long clear vinyl tube. The tube was inserted into the water column to within 200mm of the substrate, capped and removed. This enabled an integrated water column sample to be taken. In the case of Russell Street a Van Dorn sampler was used to sample depths greater than a meter. Each sub-sample was added to a ten litre bucket and thoroughly mixed. This bulked sample was then sub-sampled for filtered ( $0.45\mu$  GFC) and unfiltered water analysis. Unfiltered sub-samples were analysed for Total Phosphorus (TP) and Total Kjeldahl Nitrogen (TKN) and filtered samples for ortho-phosphate, nitrate plus nitrite and ammonia analysis. Field storage of water samples was the same as above.

### ***Sample Analysis***

All nutrient analyses were performed at ECU using a Skalar autoanalyser, with the exception of TP and TKN of the soil and plant tissue and the TKN for water samples. These exceptions were analysed by Analabs Environmental due to the unavailability of equipment at ECU. The methods are presented in Table 4.1.

### ***Data Analysis***

The duplicate bulked sample concentrations were meaned and applied to volume or mass calculations to obtain totals for the respective nutrient stores. The nutrient retention in stores was then reduced to normalised loading ( $\text{g/m}^2$ ) for comparative analysis.

Soil mass for each cell within each wetland was derived from the dry weight of soil samples to sample volume. Each cell substrate volume was calculated from the depth of core and surface area of respective cells. Surface area was defined as the area of substrate inundated. This figure was obtained from the site plans produced as a result of the mapping exercise. Total nutrient store in the substrate was then extrapolated from the mass calculation.

Plant biomass was applied to vegetation assemblage area obtained from site mapping to calculate the total mass of respective stores. Concentration apply to the total mass of vegetation derived the total nutrients retained in plant storage.

Total nutrients in the water column store was calculated from the concentration determined and estimated volume of water in each cell. Water volume estimates were part of the site mapping exercise.

Table 4.1. Methods for contaminant suite analysis of CRE and nutrient retention studies.

Analyte	Description	Method Reference
Kjeldahl Nitrogen (tissue, soil and water)	Sulphuric acid digest, steam distillation Ammonia titration.	Analabs (PEW 012)
Total Phosphorus (soil)	Mixed acid digest of pulped sample. ICP OES	Analabs (GI 201)
Total Phosphorus (water)	Sulfuric-Nitric acid digest then as ortho- phosphate.	4500-P-4b 4500-P-F (APHA, 1989)
Total Phosphorus (tissue)	Nitric, Perchloric acid digest of milled sample. ICP OES	Analabs (GI 177)
Lead (water)	Filtration, acidification, Graphite Furnace AAS	Analabs (PEMM 17)
Nitrate + Nitrite (water)	Automated Cu-Cd reduction method.	4500-NO <sub>3</sub> -F (APHA, 1989)
Ammonium (water)	Automated phenate method.	4500-NH <sub>3</sub> -H (APHA, 1989)
Ortho-Phosphate (FRP) (water)	Automated ascorbic acid reduction method	4500-P-F (APHA, 1989)
Pre-treatment - soils	dried at 105°C & pulped	
Pre-treatment (tissue)	dried at 105°C & homogenised in a bench mill.	

Note. A total of sixteen soil samples, twenty-four plant tissue samples and thirty-eight water samples were analysed for TP, FRP, TKN, NH<sub>3</sub>, and NO<sub>2</sub> + NO<sub>3</sub>. A further eighteen water samples were analysed for lead concentration.

## Contaminant Removal Efficiency Determination

### *Sampling Inflow and Outflow*

Contaminant removal efficiency was measured over a three day period at each wetland; inflow and outflow volume was recorded and sampled at each wetland. At two, four or twelve hourly intervals flow

depth and flow velocity was measured. Water samples of approximately 200 ml were taken and bulked for each twenty-four hour period. At the end of each twenty-four hour period the bulked sample was replicated into 100ml sub-samples of unfiltered water for TP, TKN and Pb analysis, and filtered sub-samples for FRP,  $\text{NH}_4$  and  $\text{NO}_2 + \text{NO}_3$  analysis. On site filtering and storage of sub-samples was as for nutrient store sampling above.

The inflow and outflow measuring stations were located at points of determinable cross-section area and where steady flow was apparent. At Bartram Road the inflow measuring station was adjacent to the WAWA monitoring station at the inlet culvert approximately 200m south-east of the constructed wetland. The outflow was measured adjacent to the WAWA outlet monitoring station at the outlet culvert (Figure 4.15). Hird Road inflow measuring was conducted at the main inlet to the retention basin of the constructed wetland system (Figure 4.9). Inflow from the second inlet was estimated from rainfall and catchment area. This second catchment was calculated from the area of road pavement draining to the retention basin. Outflow was measured at the discharge drain culvert under Hammond Road, approximately 100m south-west of the wetland discharge point. Russell Street inflow was measured at the first culvert on the Bayswater Main Drain located 100m upstream of the wetland (Figure 4.4). Outflow at Russell Street was measured at the outlet structure for the wetland. Inflows from other inlets at Russell Street were to be estimated from rainfall and sub-catchment areas. Several of these sub-catchments were too small for accurate manual measurement of inflow.

Rainfall for the study periods was measured by a 200mm rain gauge located at Bartram Road and at Russell Street respectively.

Flow volumes were determined from known cross-section area and flow velocity. These were computed for each twenty-four hour period to enable nutrient load imports and exports to be calculated. Cross referencing WAWA flow monitoring data at Bartram Road with this study's data showed a correlation of +/- 10%. This correlation was necessary to determine the accuracy of flow measurements at Russell Street that did not have continuous flow records.

### ***Sample Analysis***

The inflow and outflow samples were analysed for TP, TKN, FRP,  $\text{NH}_4$ ,  $\text{NO}_2 + \text{NO}_3$  and Pb. The analysis for TKN and Pb was performed by Analabs as described above (Table 4.1). TP analysis was the

same as for the water column analysis above. The FRP,  $\text{NH}_4$ ,  $\text{NO}_2 + \text{NO}_3$  analysis used APHA standard methods adapted to the Skalar auto-analyser as set out in Table 4.1.

### ***Data Analysis***

Concentrations for TP, FRP,  $\text{NH}_4$ ,  $\text{NO}_2 + \text{NO}_3$  were derived from a computer generated regression analysis of the relative standards curve. The concentrations were applied to the known inflow or outflow volume to calculate import and export loads for each nutrient. The loads for each twenty-four hour period were summed to give total load for the three day period of the study.

CRE for each constructed wetland was calculated as load retained as well as per cent change in concentration levels and per cent change in load. For the per cent change in concentration a mean of the three twenty-four hour levels was used.

$$\text{load retained} = \text{load imported} - \text{load exported.}$$

$$\% \text{ concentration} = (1 - (\text{outflow concentration}/\text{inflow concentration})) \times 100$$

$$\% \text{ load} = (1 - (\text{export load}/\text{import load})) \times 100$$

## ***Results***

### **Russell Street CRE, Nutrient Storage and Site Mapping**

#### ***CRE***

For the sampling period (28-31.8.95) CRE was negative for all analytes except FRP and Pb (Figure 4.2). The concentration and loading of FRP and Pb was very low for the period (Table 4.2). Daily variation in CRE was consistent for all analytes except nitrite plus nitrate (Figure 4.1). This variation in daily performance appears related to the discharge volume. Although the water budget was close to balanced for the period ( $4782\text{m}^3$  inflow to  $4775\text{m}^3$  discharge)  $2863\text{m}^3$  was discharged on day 1. Rainfall during the period was light (1mm) and did not generate measurable runoff. The flow represented runoff from previous rainfall transported via the Bayswater Main Drain. As flow decreased over the study period the CRE increased. Discharge on day 3 was  $760\text{m}^3$ . Large amounts of organic matter in the form of debris and waterweed was observed within the wetland and in the discharge drain during the sample period.

Table 4.2. Summary of Russell Street constructed wetland inputs and outputs for the period 28.8.95 to 31.8.95.

	mean in conc.	mean out conc.	Load	Load	Load	CRE
			Imported	Exported	Retained	% load
	mg/L	mg/L	Kg's	Kg's	Kg's	%
TP	0.529	0.529	2.40	2.55	-0.15	-6
TKN	0.517	0.600	2.50	2.78	-0.28	-11
FRP	0.012	0.005	0.05	0.02	0.03	54
NO <sub>2</sub> + NO <sub>3</sub>	0.412	0.645	1.98	3.28	-1.30	-66
NH <sub>4</sub>	0.082	0.117	0.40	0.59	-0.19	-49
Pb	0.003	0.001	0.02	0.01	0.01	53

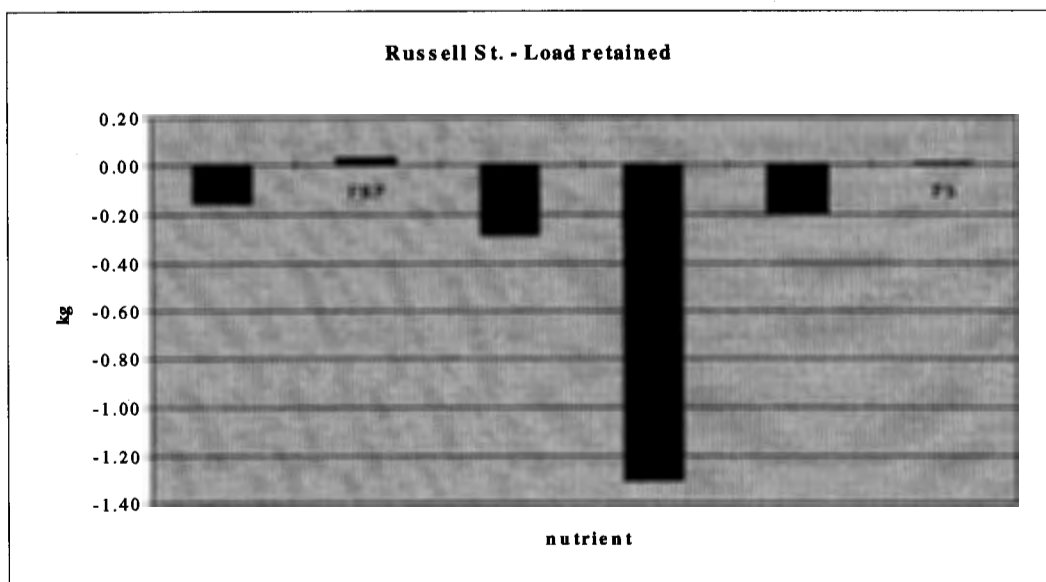


Figure 4.1. Pollutant load retained in the Russell Street constructed wetland for the period 28.8.95 to 31.8.95.



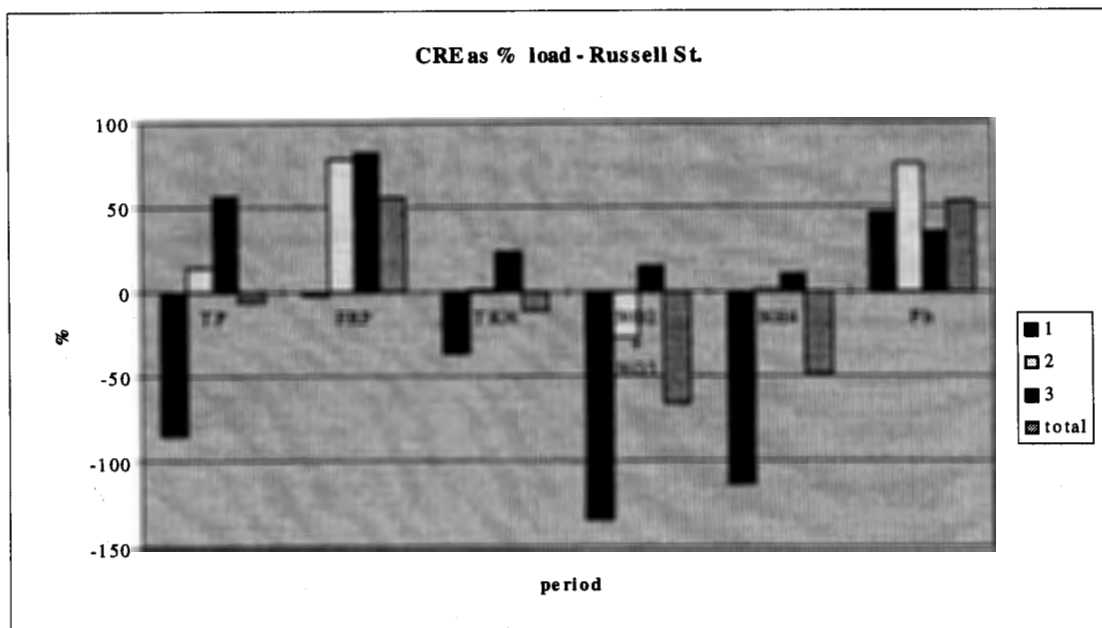


Figure 4.2. Performance variation for each twenty-four hour period compared to the summary CRE per cent reduction in load.

### Site Mapping

Prior to the nutrient retention studies being conducted it was necessary to perform site surveys to verify construction plans for surface area, vegetation area and storage volume capacity. The physical parameters of Russell Street (Table 4.3) showed no major discrepancies with the WAWA (1993) construction plan AH95-5-1. However, the position and shape of the central island had changed, being more elongated and situated closer to the inlet than the original design (Figure 4.4). The vegetation surveyed was in a narrow band fringing the open water and the island (Figure 4.4) with the fringing vegetation assemblage consisting of *Cyperus* spp., *Schoenoplectus* spp and *Juncus* spp. (Table 4.4). The *Cyperus* spp. were dormant during the nutrient retention survey. The vegetation band was located on a steep batter such that the reeds were either flooded during periods of high flow or exposed during periods of low flow. This had the effect of trapping large quantities of debris behind the reed bed when the water level receded.

The gradient of the batters appeared too steep for self-support as water action was observed to be flattening them. This was resulting in the exposed batter becoming steeper. Batter slopes were not measured but visually appeared to comply with the construction plan typical slope of 1:2.5. Spot depths taken throughout the basin indicated that the base sloped west to east with a difference in depth of 0.5m. A narrow trough approximately 3m wide and 20m long existed near the outlet on the eastern bank. This

profile did not agree with the construction plan which showed the basin divided equally into two distinct depths, with a difference in depths of 1m.

Significant scouring was observed in the basin floor at the inlet structures on the northern edge. Water erosion to the banks at the outlet structure was also apparent.

Table 4.3. Physical parameters of constructed wetlands at Bartram Road, Hird Road and Russell Street.

Constructed Wetland	Basin Aspect	Vegetation Area (m <sup>2</sup> )	Surface Area (m <sup>2</sup> )	Maximum Storage (m <sup>3</sup> )	Catchment (ha)
<b>Bartram Road</b>					
cell 1	2.5	215	2344	3010	
2	3.4	280	1050	3000	
3	3.5	7812	10312	18800	
4	7.5	11563	16250	20500	
5	2.8	340	2812	3800	
Total		20210	32668	49110	1050
<b>Hird Road</b>					
1	1.3	98	1200	840	
2	4.2	2650	22500	15000	
Total		2748	23700	15840	120
<b>Russell Street</b>					
1	2	480	6400	12000	40

### ***Nutrient Storage***

The nutrient store analysis determined total storage for TP and TKN as 27kg and 90kg respectively (Figure 4.3a). The dominance of the substrate as a store was also reflected in ratio to the total nutrient storage, that being 74 % for TP and 89% for TKN (Figure 4.3b). Normalisation of the total store to g/m<sup>2</sup> reduced that dominance showing the retention capacity of the plant store to be more eminent (Figure 4.3c).

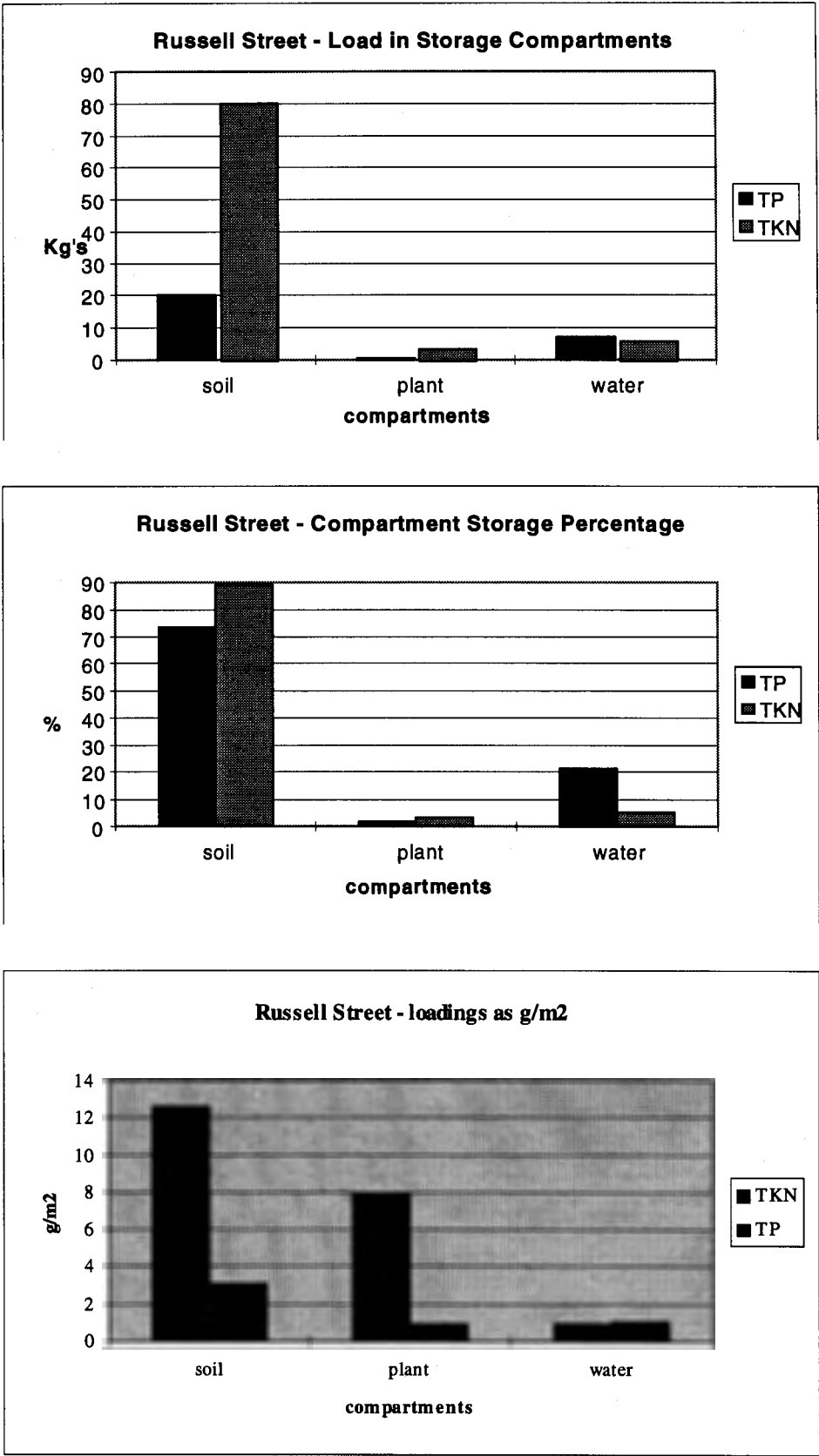


Figure 4.3. Russell Street TP & TKN stores as total storage (a), per cent of each store of the total (b) and as g/m<sup>2</sup> (c).

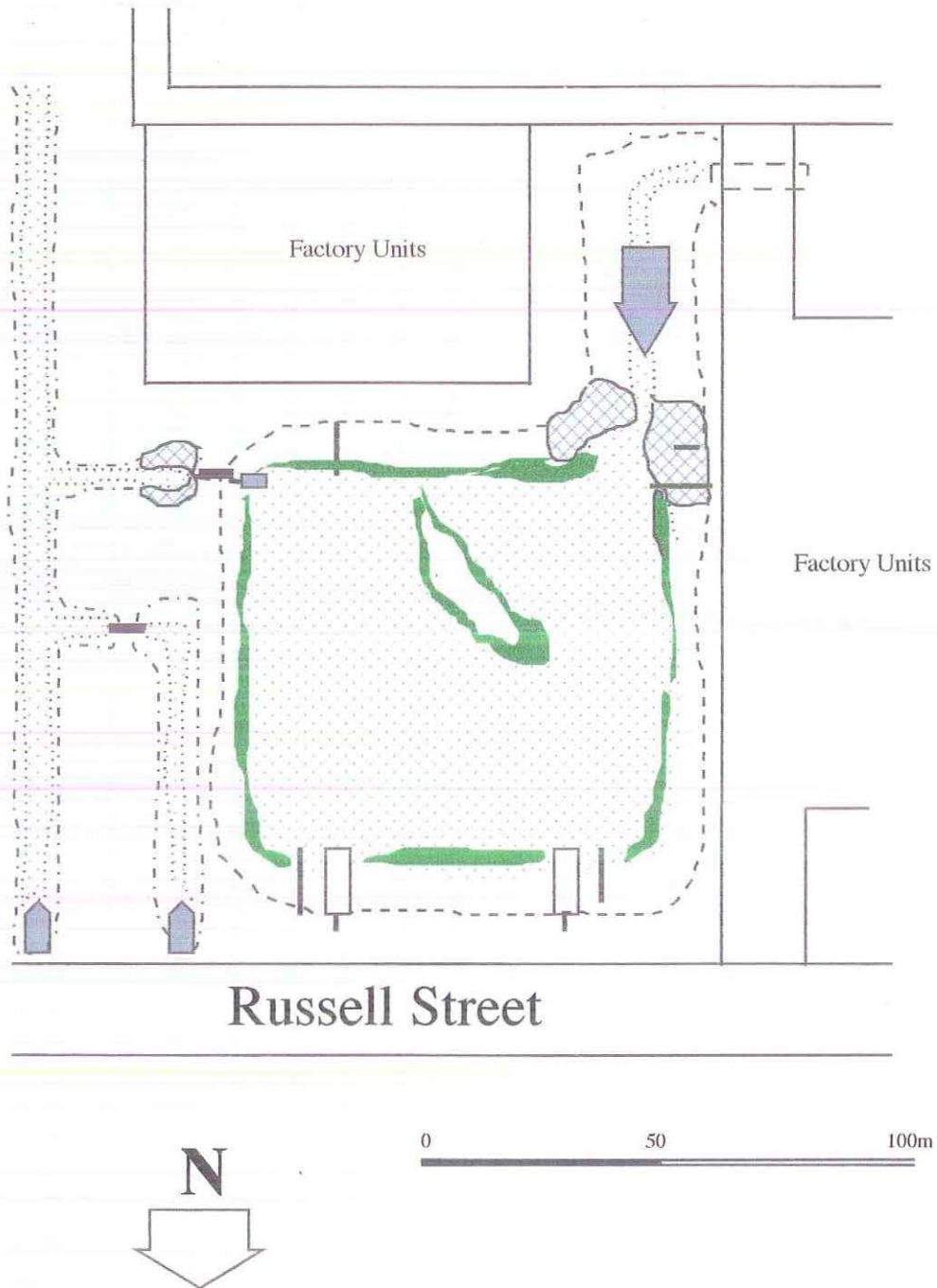


Figure 4.4. Russell Street Biofilter. An existing drainage compensating basin modified for nutrient stripping functions. The island provides an aspect ratio of 2:1. *Juncus* spp. have been planted in a 2m strip around the basin and over the island. Maximum storage is  $12000\text{m}^3$  with a surface area of  $6400\text{m}^2$ .

Table 4.4. Plant species list for Bartram Road (B), Hird Road (H) & Russell Street (R) wetlands. The plant species listed constitute the edge and Baumea plant assemblages. The herbaceous species are all edge assemblage while in the sedges (F) designates edge assemblage (I) the Baumea assemblage. Woody species listed are all subject to periodic inundation and typically occur on the wetland fringe.

herbaceous species	B	H	R	Reed, rush & sedges	B	H	R	Woody spp.	B	H	R
<i>Callitriche stagnalis</i> (common starwort)	•			<i>Cyperus eragrostis</i> (F) (umbrella sedge)	•	•	•	<i>Melaleuca raphiophylla</i> (freshwater paperbark)	•	•	••
<i>Pennisetum clandestinum</i> (Kikuyu grass)	•	•		<i>Cyperus exaltatus</i> (F) (umbrella grass)	•	•	•	<i>Melaleuca lateritia</i> (robin redbreast bush)	•		
<i>Isolepis prolifera</i> ( <i>Scirpus prolifer</i> )	•	•		<i>Juncus acutus</i> (F) (spiny rush)	•			<i>Melaleuca teretifolia</i> (Banbar)	•	•	
<i>Lemnaceae</i> spp. (duckweeds)	•	•	•	<i>Schoenoplectus validus</i> (F) [ <i>Scirpus validus</i> ] (river clubrush)	•	•	•	<i>Eucalyptus rudis</i> (moitch - flooded gum)	•	•	
				<i>Baumea articulata</i> (I) (jointed twigrush)	•	•		<i>Agonis linearifolia</i> (swamp peppermint)	•	•	
				<i>Juncus pausiflorus</i> (F)	•	•	•	<i>Astartea fascicularis</i> ?	•	•	
				<i>Juncus pallidus</i> (F) (pale rush)	•	•					
				<i>Lepidosperma effusum</i> (F-I) (spreading sword-sedge)	•	•					
				<i>Lepidosperma longitudinale</i> (F) (pithy sword-sedge)	•	•		* spp. subject to manual removal			
				<i>Typha orientalis</i> (I) (cumbungi)	•	•	*	•• spp. recently planted			
				NO id, fine, terete reed, large (F) (I) tussocks (native)	•	•		(saplings)			

Hird Road CRE, Nutrient Storage and Site Mapping

CRE

The CRE of Hird Road for the period had contradictory results. When expressed as per cent reduction in flow concentration, the CRE was positive for all analytes except FRP, however when the CRE is expressed as per cent reduction in load, the result was negative in the extreme (Table 4.5). The apparent contradiction is a result of the water budget imbalance on drain inputs and wetland discharge during the study period. Total inflow recorded was 191m<sup>3</sup> against 1998m<sup>3</sup> discharge. Groundwater inputs were not taken into account. Rainfall contributed approximately 200m<sup>3</sup> directly to the wetland however no analysis was performed on the rainfall sample (see Bartram Road CRE). The imbalance in favour of discharge volume provided the opportunity for greater export of nutrient loads than imports. None of the analytes had retained load and the wetland acted as a source of nutrients during the study period (Figure 4.5).

The concentration of lead in inflow and outflow waters was less than the detection limit of 0.001mg/L.

Table 4.5. Summary of CRE for Hird Road constructed wetland for the period 18.8.95 to 21.8.95.

Analyte	mean in conc	mean out conc.	Load Imported	Load Exported	CRE	CRE
	mg/L.	mg/L	Kg's	Kg's	% conc.	% load
TP	0.625	0.551	0.13	1.10	12	-758
FRP	0.930	1.388	0.19	2.77	-49	-1391
TKN	1.117	0.917	0.21	1.83	18	-774
NO <sub>2</sub> + NO <sub>3</sub>	0.542	0.154	0.10	0.31	72	-200
NH <sub>4</sub>	0.613	0.107	0.11	0.21	83	-88

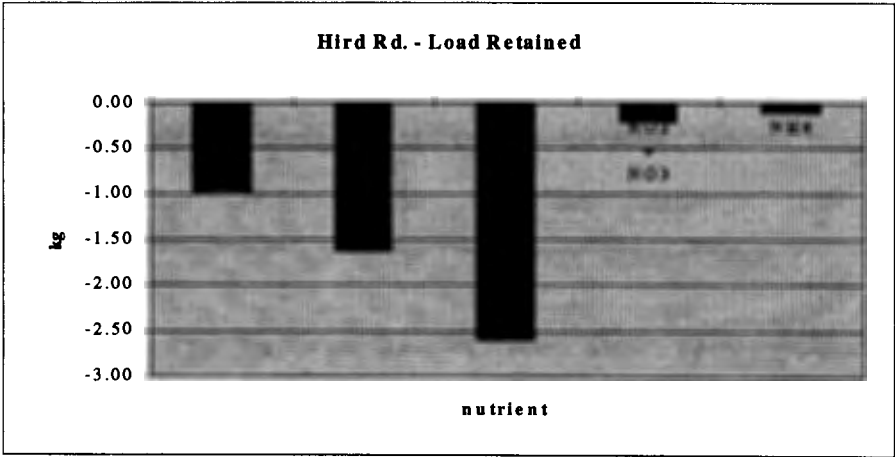


Figure 4.5. Nutrient load retention in the Hird Road constructed wetland for the period 18-21.8.95.

### ***Site mapping***

No construction plans were available to compare site mapping data measured and collected (Figure 4.9).

There were several physical features of this system that may effect performance criteria. The first was the location of the small culvert (300mm) connecting the constructed cell (Figure 4.9 (1)) with the natural wetland area (Figure 4.9 (2)). This reduced the effective flow path of the natural wetland by an estimated one third. Second, the locations of the inlets and outlet to the constructed cell suggest that a circular flow could be generated. Third, spot depths taken to estimate volumes indicate that the constructed cell has an even depth of approximately 1m. This cell appears to have permanent groundwater that is at the same level as the natural wetland. Fourth, a formal park, maintained by the local council surrounds this cell and forms the eastern perimeter of the natural wetland. There is no buffer vegetation surrounding the park. Fifth, the south-west and north-west corners of the natural wetland are relatively undisturbed areas and have a diverse vegetation assemblage (Table 4.4; Figure 4.9). The basin of the natural wetland cell is flat with a maximum depth of one metre and an average depth of 0.7m. The physical parameters of the system are detailed in Table 4.3.

Sixth, the impact of the sewer line construction (Figure 4.9) on the southern perimeter was apparent in the regeneration growth of vegetation in that area. Typical wetland macrophyte vegetation was absent from the north and eastern perimeters of the natural wetland. Seventh, anecdotal history supplied by the current landowners informed me of land use that included battery hens and a piggery in recent times. Also goat herds were allowed to graze the wetlands. This severely degraded the natural vegetation allowing the Kikuyu (Table 4.4) to established on the northern perimeter. The locals also reported that the wetland usually dried out during late summer but this had not occurred since draining stormwater to this wetland commenced. Similarly the discharge from the wetland has increased causing an increase in area and time that the downstream neighbouring property is inundated. The local residents report no consultation on the intention to drain runoff to the wetland or on the possible impacts of that action.

### ***Nutrient Storage***

The total nutrient store at the Hird Road wetland was 143kg TP and 2351kg TKN (Figure 4.7a & 4.8a).

The substrate was the dominant store contributing 73 % of TP and 96% of TKN totals (Figure 4.7b & 4.8b). In terms of total storage, the constructed cell (#1) contributed little (Figure 4.9 a & b). This was

not simply a reflection of the small area involved (Table 4.3) as the stores were still small even when normalised to  $\text{g/m}^2$  (Figure 4.7c & 8c). The effect of area of total storage was apparent with the plant store in normalised data where the plant store was 78% that of the soil  $\text{g P/m}^2$  (Figure 4.7c) although this was not the case for TKN (Figure 4.8c).

The effect of the sewer line construction (Figure 4.2) was evident in substrate cores taken in the south-west corner of the wetland. The cores in the immediate area had a coarse sand profile compare to peat profiles elsewhere in this cell. The profiles of cores taken in the first cell were coarse sand with a cover of thin silt. The difference in phosphorus storage capacity between sandy substrates and either red mud amended or peat soils (Figure 4.6) indicates that the disturbance caused by the sewer construction contributed to reduced storage capacity of the substrate.

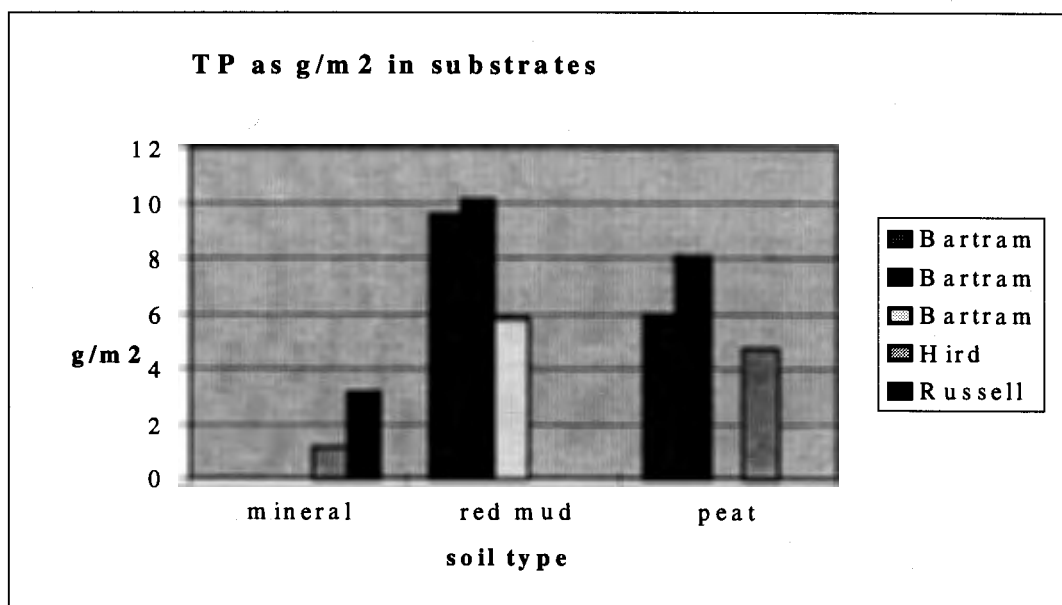


Figure 4.6. Comparison of substrate Total Phosphorus storage capacity as  $\text{g/m}^2$



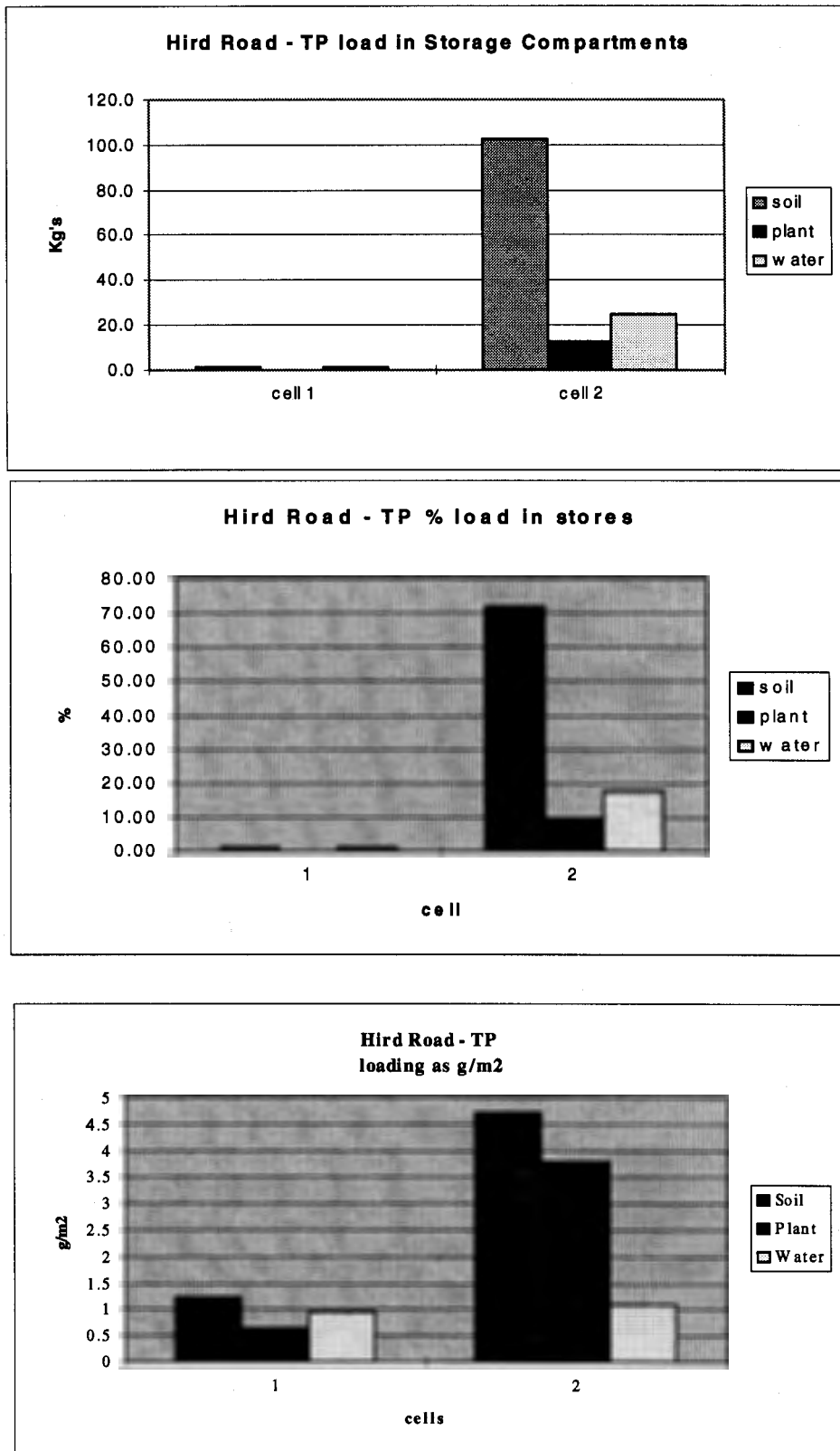


Figure 4.7. Hird Road Total Phosphorus stores as total storage (a), per cent of each store of the total (b) and as g/m<sup>2</sup> (c).

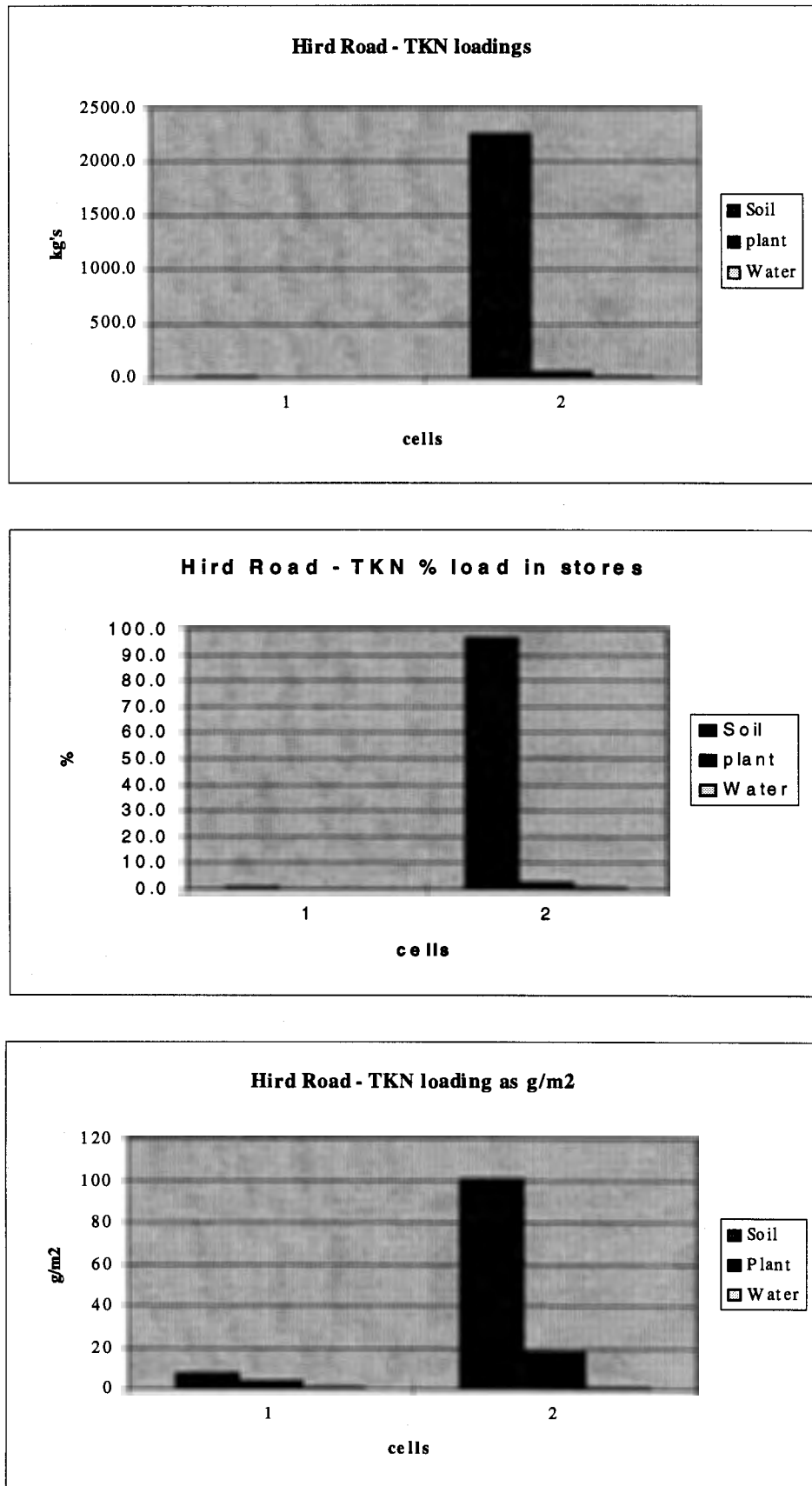


Figure 4.8. Hird Road Total Kjeldahl Nitrogen storage as total storage (a), per cent of each store of the total (b) and as g/m<sup>2</sup> (c).

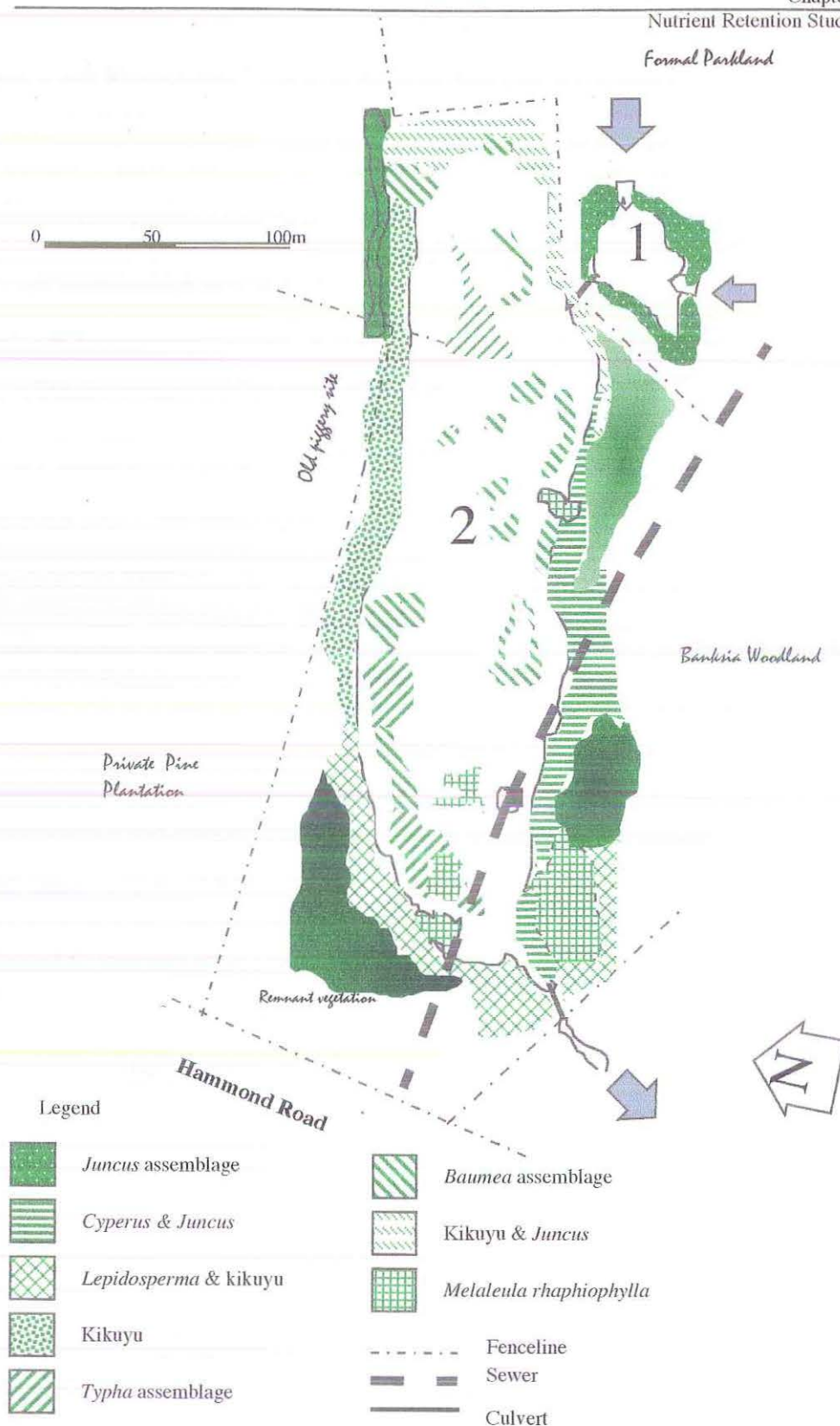


Figure 4.9. Hird Road Buffer Lakes. Cell 2 is a degraded natural wetland while Cell 1 has been constructed as a retention basin for the system. The more diverse vegetation assemblages occur in the relatively undisturbed NW and SW corners.

## Bartram Road CRE, Nutrient Storage and Site Mapping

### CRE

Over the 72 hours there was a net retention of all analytes except Total Phosphorus (Table 4.6, Figure 4.10). The water budget for Bartram Road during the study period was not balanced with 8977m<sup>3</sup> of runoff inflow and a discharge of 8309m<sup>3</sup>. Rainfall was light for the study period (8.8mm) and contributed an estimated 250m<sup>3</sup> directly to the wetland area. Analyte analysis of the rainfall was not possible due to contamination from bird droppings.

Daily variations in CRE as per cent reduction in load for Total Phosphorus (TP) ranged from -95%, -96% to 31%. The opposite trend was apparent with FRP (Figure 4.11). For FRP to be retained indicates that transformation is taking place.

Daily variation in nitrogen CRE was not as apparent as for phosphorus (Figure 4.11). Although TKN CRE at 15% is a moderate performance, converting Total Kjeldahl Nitrogen (TKN) and Nitrate plus Nitrite (NO<sub>2</sub>+NO<sub>3</sub>) to Total Nitrogen (TN) showed an effective TN CRE in load of 30% (Table 4.6).

Lead loadings and concentrations are not listed as although analysis detected traces there was less than the determinable limit of 0.001 mg/L.

Table 4.6. Summary of loads and concentrations for Bartram Road constructed wetland for the period 18-21.8.95.

Analyte	Mean inflow conc. (mg/L)	Total Load Imported (kg)	Mean outflow conc. (mg/L)	Total Load Exported (kg)	Load Retained (kg)	CRE % reduced. load
TP	0.507	4.58	0.829	6.73	-2.16	-47
FRP	0.341	3.04	0.270	2.27	0.77	25
TKN	1.433	12.85	1.317	10.88	1.96	15
NO <sub>2</sub> +NO <sub>3</sub>	0.321	2.88	0.016	0.130	2.76	96
<sup>3</sup> NH <sub>4</sub>	0.057	0.50	0.055	0.46	0.04	7

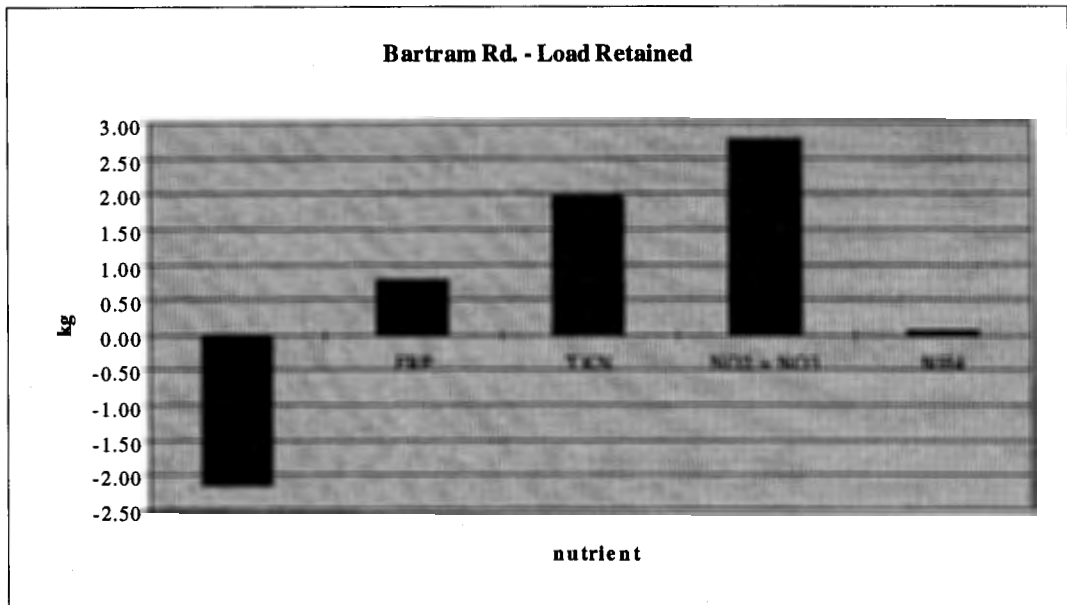


Figure 4.10. Bartram Road constructed wetland nutrient load retention for the period 18-21.8.95.

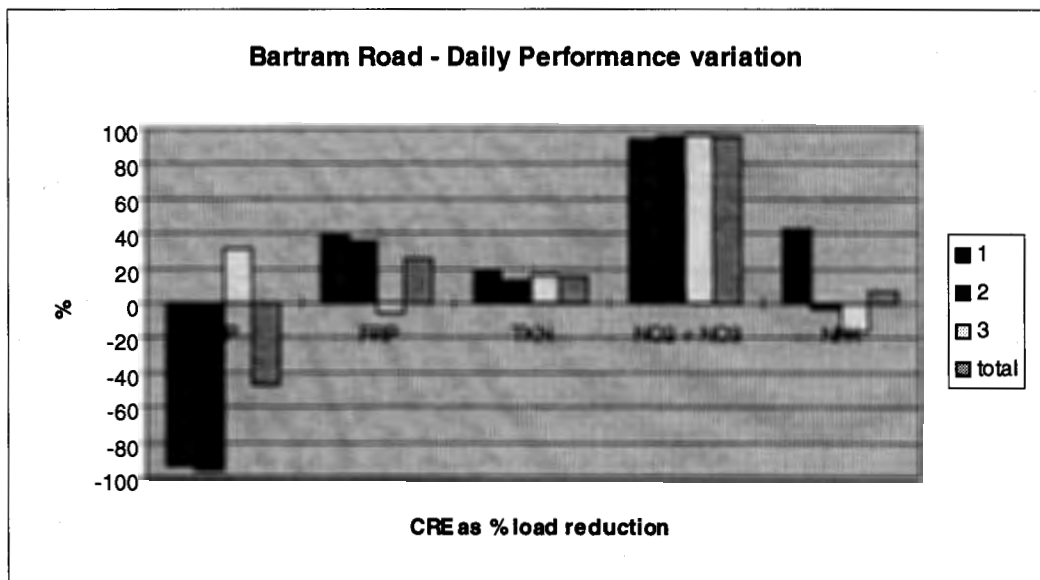


Figure 4.11. Daily performance variation and summary CRE as % reduction in load for Bartram Road during the period 18-21.8.95.

### Site mapping

There was general agreement between physical parameters (Table 4.3; Figure 4.15) measured and those in constructed plans (WAWA CT90-1 to 4). There was a difference in the positioning of the connecting drain between cell 2 & 3 and the headland supposedly opposite. The headland is smaller and not angled against the inlet as designed (Figure 4.15). Flow from cell 2 is not deflected by headland. Dead zones

created by the positioning of connections between cells (2-3, 3-4 & 4-5) result from construction as per design (Figure 4.15).

The design did not specify techniques for translocating *Baumea* to other cells. As a result efficient construction procedures removed all required *Baumea* in a strip adjacent to the bund construction in cell 4. This created a channel for water flow in this cell (Figure 4.15).

The vegetation survey (Table 4.4) showed the Bartram system to have the most diverse plant assemblage of the three sites studied. The dominant assemblage was *Baumea articulata*. The fringing plant assemblage was more diverse than the planting guide for the system indicated. The guide listed only two species (*Juncus pauciflorus* & *Schoenoplectus validus*) and it was not established whether the increased diversity resulted from design amendment or recruitment from neighbouring wetlands. The *Cyperus* spp. were vigorous at the time on the site survey but dormant during the nutrient retention study. The reverse was true for *Callitriche stagnalis* and Lemnaceae which were prolific in cells 1 & 2 during this study. Also, algal scum was observed trapped in reed beds of all cells.

Bartram Road has a significant portion of the system as natural wetland (Figure 4.15 - cells 3 & 4). Anecdotal evidence reports that this area was used for waste disposal as well as a horse grazing and riding trail area.

### ***Nutrient Storage***

The TP storage for all compartments was 347kg (Figure 4.13a). The substrate was the dominant store with 69% of the total (Figure 4.13b) while the plant and water stores had an equal per cent contribution. However when the load data is normalised to g/m<sup>2</sup> the plant store is more prominent than the water store (Figure 4.13c). This trend was repeated for TKN with the storage for all compartments 2758kg (figure 4.14a.), the substrate store being 88% of this total and plant store at 10% (Figure 4.14b).

In two of the cells, the first and last, plant TKN store as g/m<sup>2</sup> exceeded the g/m<sup>2</sup> loading of substrate (Figure 4.14c). This trend was not observed for TP, which was higher in the sediment in all cells (Figure 4.13c).

During coring of the substrate it was noted that the red mud amended substrates in cells 1, 2 and 3 exhibited uneven composition. In some areas the red mud had coagulated to form a very hard layer

while in others the profile was as easy to penetrate as the mineral sands. Examination of the core profiles revealed variable mixing of the red mud through the profile. In the profiles taken in the natural wetland cells close to the central bund (Figure 4.15) the effect of construction was still evident with coarse sand overlaying peat. The retention capacity of different substrate types was noted in the comparison of  $\text{g P/m}^2$  of the substrates encountered at the three wetlands (Figure 4.6). Observation during the nutrient store sampling noted that the red mud was easily re-suspended and remained suspended for a considerable time. This problem was also apparent by the amount of red mud washed into the basins by relatively minor embankment run-off generated by the light rains.

*Baumea* assemblages dominated the plant nutrient storage not only at Bartram but also at Hird Road. However when this data was normalised a high retention capacity existed for the edge plant assemblage in cell 1 (Figure 4.12). The profilic growth of *Callitriche* and *Lemnaceae* in this cell could account for the high P store.

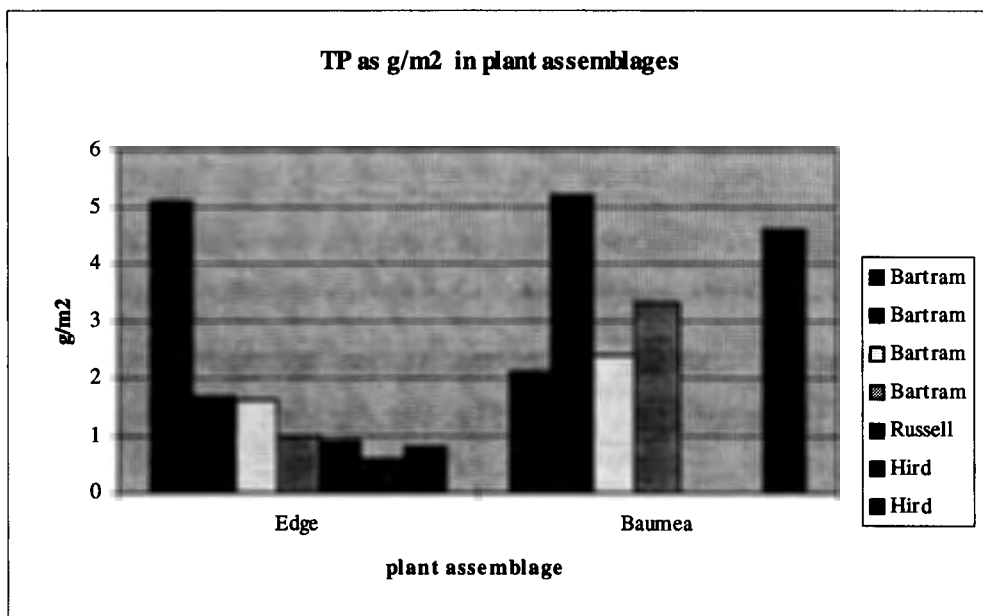


Figure 4.12. Comparison of TP as  $\text{g/m}^2$  in plant assemblages at all the constructed wetland sites.

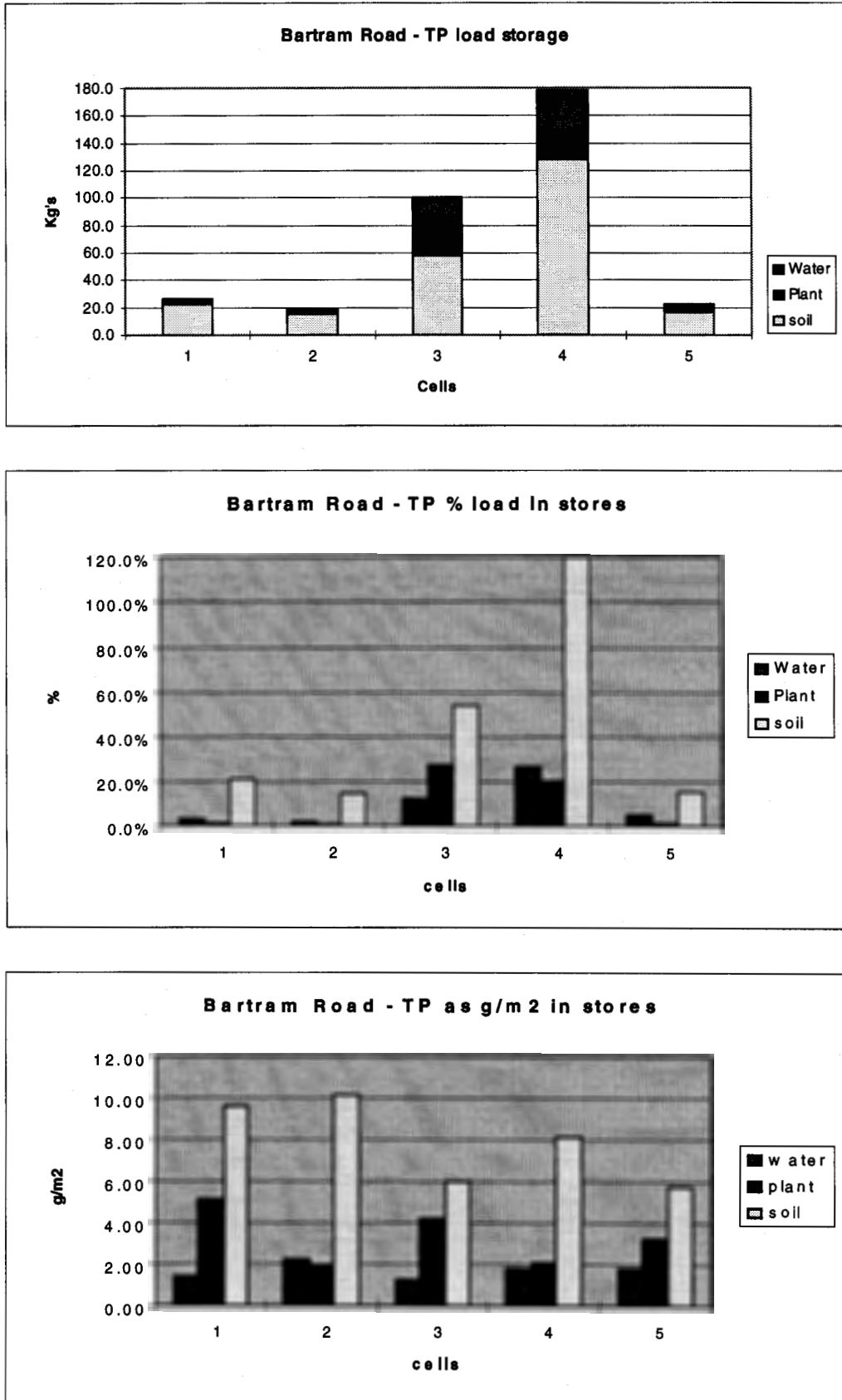


Figure 4.13. Bartram Road Total Phosphorus stores as total storage (a), per cent of each store of the total (b) and as g/m<sup>2</sup> (c).



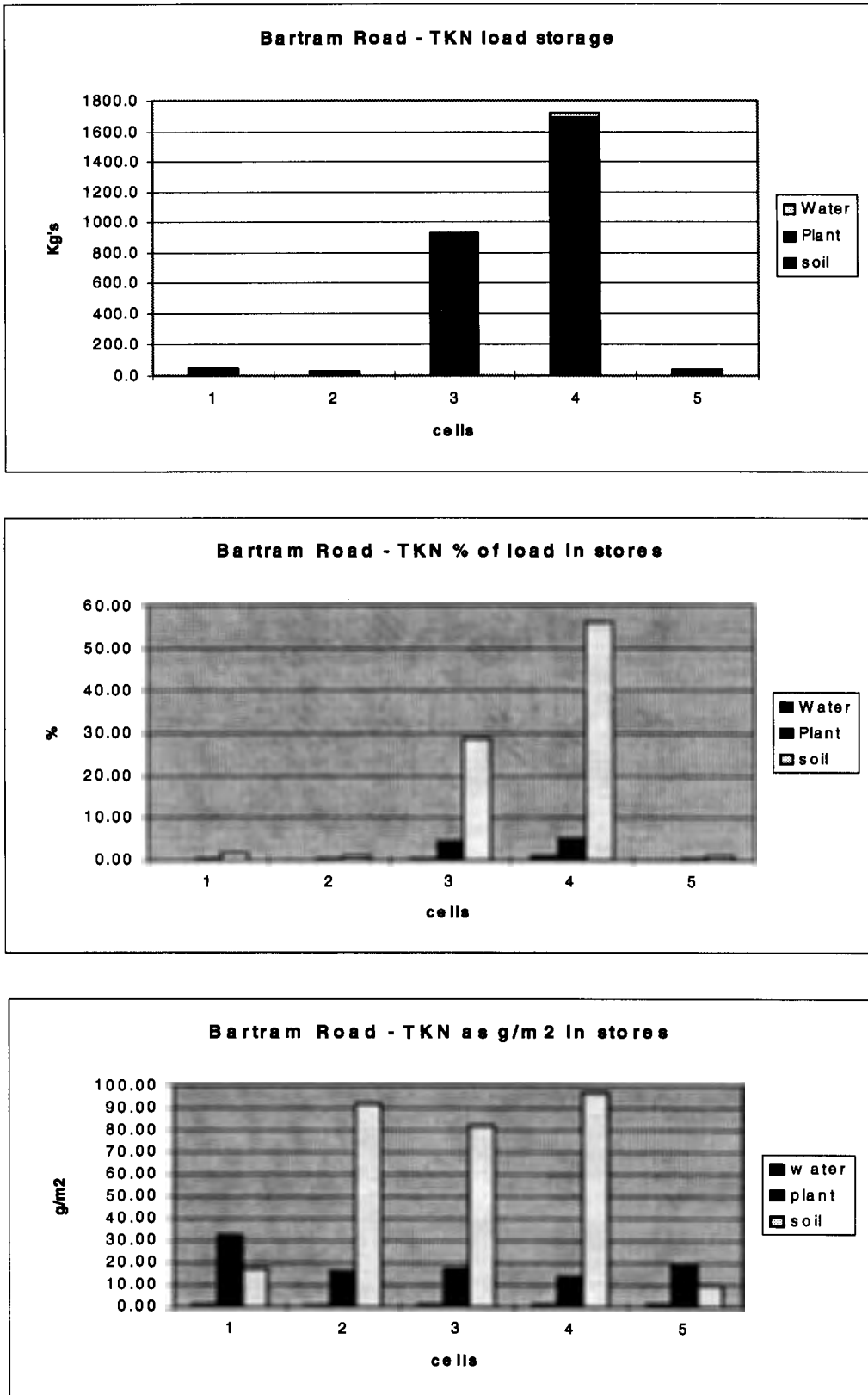


Figure 4.14. Bartram Road Total Kjeldahl Nitrogen stores as total storage (a), per cent of each store of the total (b) and as g/m<sup>2</sup> (c).



Figure 4.15. Bartram Road Buffer Lakes. Vegetation assemblages at this wetland were the most diverse of the study sites. Note the channel created by transplanting *Baumea* from alongside the central bund in cell 4. Also note the dead zones in cell 3, 4 & 5 created by the location of cell connections.

## ***Discussion***

The aim of the nutrient retention studies was to compare the performance of each wetland against their design elements as an indicator of effective CRE design. Given that none of the constructed wetland systems met their primary objective of effective Total Phosphorus (TP) removal during a short period of low to moderate rainfall, all of the designs need to be questioned. However, the CRE determination process in itself provides some of the answers to the recorded performances.

Bartram Road was effective in nitrogen removal (30%) but was contradictory in while there was phosphate retention (FRP) there was a net export of TP. Two possibilities could explain this phenomenon. First, the phosphates are transformed to particulate form via uptake from phytoplankton or zooplankton and then discharged and detected as TP. Second, re-suspended red mud particles high in phosphorus are being discharged and detected as TP. Similar variation in phosphorus retention recorded at Russell Street could also be explained as phosphate transformation and discharge in particulate form. The discharge structures at all the study sites had areas of open water immediately prior to them. This suggests that outlets should have filters that can trap particulate matter generated by the wetland system. Ideally, the discharge cell should be densely vegetated with swale drains directing the discharge flow to an outlet structure.

In assessing the individual wetland nutrient removal performance per cent reduction in concentration was a misleading statistic. At Russell Street the high per cent CRE of phosphate and lead needed to be related to the total load of those pollutants. Both were so small that any reduction detected represented a large percentage decrease. Hird Road inflow and outflow concentrations indicated a positive CRE, however when loads were considered, the wetland acted as a source of pollutants during the study period. This was reflected in results of CRE from all the wetland sites. Bartram Road had an imbalance in the water budget with more input than output which favoured a positive CRE result, Hird Road was the reverse, with greater discharge than recorded input which favoured a negative CRE. The study suggests therefore that performance evaluation should only be performed on a balanced water budget.

Groundwater contributed to all wetland sites but was not quantified and as such it was not known whether it diluted or concentrated surface flows. Flow data for Hird Road (Fuller & Deane, 1995) indicates that two thirds of water budget is groundwater contribution and a similar contribution at

Russell Street is indicated by the design for permanent water levels (WAWA, undated). The significant contribution of groundwater in the study sites contradicts the lack of importance of this element to wetland performance attributed to it by Duever (1988). The groundwater contribution must at least be estimated to allow an accurate performance evaluation.

A problem in performance evaluation is indicated by the some of the dramatic variations in daily performance figures calculated during this study. As discussed above the variation in performance can be related at least in part to the variation in flow volumes. Given the limited temporal scale of the study this variation is similar to that reported by Meiorin (1989) and Rueter et al. (1991) resulting from severe storm events in Californian wetlands. While it is inadvisable to extrapolate figures from such a limited study, the study suggests that overall performance evaluation needs to be determined by summing load retention on the smallest feasible time scale.

### **The Need for Detailed Site Assessment**

The above discussion provides an explanation for at least a portion of the poor performance evaluation. The following discussion on site designs provides a further insight.

First, managers of the respective wetlands would not know if it was design inadequacies or alterations to design during construction that were contributing to the poor performance. There are no plans available for Hird Road and no complete compliance assessments for any of the projects studied. The “as constructed” for Bartram consisted of a check on culvert levels within the system. Bartram Road had changes that are significant to the performance of the wetland. As referred to in the results for Bartram, a creation of a channel through the dense *Baumea* stands in Cell 4 causes short-circuiting of the flow path through this major cell. In addition, the alteration to the shape and location of the headland in cell 3 causes short-circuiting of the flow in that cell. The discussion in chapter 3 indicated that the *Baumea* translocation in cells 2 & 5 had been unsuccessful and this also reduced residence time within those cells. The lack of dense reed beds in those cells was illustrated in the site plan for Bartram Road.

The site mapping conducted for this study was originally intended to relate to the comprehensive assessment requirement of constructed wetland management discussed in chapter 2. However the mapping had to fulfil the requirements of an “as constructed” survey such that the individual wetland development was not able to be determined. However, the mapping was invaluable in conducting the

design critique and subsequent management recommendations in the case studies of chapter 2. The mapping highlighted several design flaws that reflected in the performance evaluation and the flow studies of the previous chapter.

Briefly restated they are; channel flow created by culvert and ditch connections between wetlands at Bartram and Hird, a reduction in flow path and effective surface area through poor inlet location the potential for channelling of flow through expanses of open water. In addition the importance of flat basin profiles was apparent at Russell Street where the narrow fringing vegetation belt could influence removal functions only when it was flooded during high periods. That influence was negated by the short residence times of the Russell Street system during those periods of high flow.

### **The Need to Consider Nutrient Stores in Wetland Design**

This study suggests that the strategy of designing deep open water basins to reduce the area requirement of the wetland (Hammer & Knight, 1992) and as an effective settling pond for particulates (Evanglisti, 1994) is counter-productive. Not only do they provide a potential for short-circuiting, but they increase the loading rate to the substrates and reduce the potential plant store (Chambers & McComb, 1992).

When considering substrate or plant components of the wetland as nutrient stores this study confirmed that the composition and the area are critical factors. This was indicated in the normalised data (g/m<sup>2</sup>) of both stores.

The results of the substrate analysis indicated higher retention capacity in amended soils such as red mud or peat than the mineral sands in the constructed cell at Hird or Russell systems. The total store calculations also indicate that increasing surface area significantly increases the total storage capacity. This factor can be exploited with flat basin profiles. Hird and to a lesser extent the Bartram system are able to increase the surface area with an increase in water volume without significantly changing the depth of water. This increases the nutrient storage capacity of the wetland at times of peak flow. However, the steep banks at Russell Street can only minimally increase available storage during peak flows. This leads to an increase in loading to the stores and may lead to saturation of stores more quickly, that in turn may effect immediate performance and reduce the effective life of the system.

Artificial compounds used for soil amelioration need to be thoroughly researched before their use. The observed problems arising from the use of red mud support findings by Sampson (1994) on studies on the use of red mud in sewerage treatment ponds. In this study it was noted that red mud had a tendency to clog and become impervious. In Sampson's study this problem was overcome by using the similar bauxite by-product of red sand. Sampson noted that red sand has a higher fraction ( $>150\mu$ ) that prevented clogging and is twenty per cent more effective in phosphorus adsorption due to its higher permeability. When these data are coupled to observations of poor plant establishment in red mud amended soils it is recommended that red mud not be used in soil amelioration of constructed wetland projects since even with its higher PRI, its resuspension and clogging properties render it relatively ineffective. Given the observed benefits of soil amelioration in this study it is recommended that future projects research the use of red sand, crushed limestone (Kayalp et al., 1988) or industrial slag (Mann & Bavor, 1993) as a means of increasing nutrient storage capacity in substrates.

Perhaps the most neglected component relating to wetland design is the potential contribution to performance enhancement and nutrient storage capacity of wetland vegetation. Observations of this refer to a limited number of species but indicate a potential to enhance CRE of wetlands within design constraints imposed by area availability.

The *Baumea articulata* plant assemblage formed the densest stands and as such contributed most to the plant storage pool. Floating plant species such as the common starwort (*Callitriche stagnalis*) and duckweeds (*Lemnaceae spp.*) formed dense mats of vegetation and significantly contributed to storage pools in cells where they were prolific. These floating species appear to offer a significant nutrient retention pool but such plants would require harvesting and discharge traps to prevent clogging or downstream export. *Isolepis prolifera* was also a vigorous plant during the study period but was not so during mapping two months earlier. The umbrella grasses (*Cyperus spp.*) exhibited the opposite growth pattern and were dormant during the study period. Painful personal encounters with the spiny rush (*Juncus acutus*) suggest that this species is not suitable for areas that have public access to the wetland.

The normalised data ( $\text{g/m}^2$ ) on plant assemblages presented in the results section indicates that plant stores are significant but the absence of large stands makes them a minor contributor to the total store. It would seem that the neglect of plant stores in design considerations stems from the belief that they are

only short term stores, recycling their stored nutrients on a seasonal basis. Appropriate design of discharge structures would prevent the export of decayed plant material as particulate matter. This would enable plant assemblages to play a more prominent role in nutrient stripping. That role would not only be as a store but control of flow patterns as noted in the Rhodamine WT studies and increase the potential for nutrient uptake and transformation due to an increase in the soil-water-plant interaction. All three study sites would benefit from an increase in vegetation area and density.

## **Chapter 5**

### **General Discussion**

#### ***Implications of the findings in this study to the design criteria of constructed wetlands***

Constructed wetlands are viable as treatment strategy to reduce stormwater pollution and they offer the potential of multi-purpose sites. This conclusion was drawn for the synthesis of data in the literature review however, it appears to contradict the results of the field data. The design critique conducted in Chapter 2 showed this apparent contradiction to be the result of an inconsistent approach to the design process that allowed inappropriate design elements to be incorporated into the respective wetland projects. The design process detailed in Chapter 2 is outlined similarly to the research questions formulated to structure and focus this study:

1. Identify what the pollutants are, their form and what loadings are expected (RQ1),
2. Identify the objective and determine the level of treatment (CRE) (RQ6),
3. Determine whether wetlands are a viable option as a treatment for the problem (RQ2),
4. Assuming a wetland is viable, determine the wetland functions to achieve the required CRE (RQ3),
5. Design the wetland elements required to perform the defined functions (RQ4) and
6. Design the review and management procedures to ensure that the conditions of 4 & 5 are being maintained (RQ5).

This process appears obvious and simple, yet none of the sites examined in this study satisfied the complete process. The review of literature also suggests that this is the case in a large percentage of wetland projects. Stage 6 is most commonly absent, followed by Stage 1 which then makes it difficult to



align suitable removal functions with design elements. The first step in achieving consistent constructed wetland success is to adopt a consistent strategy (design process).

The results of the field assessments for each of the study sites provided an explanation as to why each wetland was performing in the manner it was. This supports the general statement in literature that constructed wetlands systems do not fail; they adjust, develop and perform according to their exposure to prevalent conditions. If they do not meet CRE objectives then it is the design that has failed to supply the required wetland elements to enable the system to perform the desired functions. This is almost an abstract notion that requires a change in thought from the traditional technical solutions that involved installing hard engineering type solutions which isolated and alienated the structures from their immediate environment. Each wetland element has to be considered not only as a single unit but also as a part of the all system and vice versa. This stresses the need for integrated management perspective and a multi-disciplined project team as suggested by Wilcox (1988) and Wetzel (1993).

### **Specific Findings and Recommendations**

The study found that there is not a single “recipe” of design criteria that will fit all situations. Rather effective design criterion is determined by satisfying all the phases of a design process. The “recipe” as such develops from that process.

The three wetlands studied here are considered unsuccessful for the following reasons: contaminant removal objectives were not met, design residence times were not met and general design criteria was not satisfied. Hence, the findings and recommendations that follow are based on ‘what not to do’.

It is recommended that wetland design be sufficiently flexible to remove pollutants in either particulate or dissolved form. This need was apparent during the review of stormwater characterisation (Chapter 2.2). Many designs fail because the pollutants in stormwater were assumed to be in particulate form. When particulate removal forms the strategy for wetland design but the pollutants are in dissolved form, then it is likely the wetland will not meet the design objectives. The reverse is also true. The studies on Bartram and Hird suggested that internal wetland processes transform pollutants from one to the other. The nature of stormwater runoff will vary with each catchment and that nature needs characterisation for each catchment.

A major failing of wetland design reviewed was the compromise of wetland elements to meet commercial, economic or social conditions. The need to compromise may be viewed as a fact of life. However, natural processes are uncompromising. If all of the elements required to perform a particular function are not present, then that function will not operate effectively and may not operate at all. The physical parameters mapped at the Russell Street system place it in the above category. The major compromise was found to occur in storage and surface area requirements. Optimum design criteria allows for sufficient storage to meet residence time requirements of peak flows. Wetlands designed for lesser flows risk detrimental effects on the structure of the wetland during peak flows. Also these wetlands will have reduced performance efficiency due to the high percentage of pollutant export that occurs during the peak flows. In addition, designs based on average flows risk being insufficient for at least 50% of rainfall events. Average rainfall typically represents extremes of weather conditions and is rarely actually recorded. It is recommended that design cater for peak flows to reduce problems arising from inadequate storage.

The surface area requirement is a rule-of-thumb expression of the loading retention capacity. Compromising on that requirement leads to a higher loading intensity on the wetland that reduces removal efficiency and shortens the effective storage life of the wetland. In order to estimate loading rates it is necessary to determine the nutrient retention capacity of the particular substrate being used. Wastewater constructed wetlands produce consistent results basing the design on loadings but it is not often used as a parameter for stormwater treatment. The variable success rates reported for stormwater indicates that this parameter is most likely the most critical in achieving success. More research in to the effect of loading in stormwater wetlands is required.

This study suggests that the strategy of designing deep open water basins to reduce the area requirement of the wetland (Hammer & Knight, 1992) and as an effective settling pond for particulates (Evanglisti, 1994) is counter-productive. Not only do they provide a potential for short-circuiting, but they increase the loading rate to the substrates and reduce the potential plant store (Chambers & McComb, 1992). The design must align with the primary objective and must not be compromised to meet secondary objectives. Large expanses of open water may be desirable as a landscape feature or for mosquito control but they do not promote plug flow. Flow studies in all three wetlands suggested that the short-circuiting

recorded was at least in part caused through establishment of channels in open water. It is recommended that design criteria avoid deep open water areas.

Culverts and trenches used as inlet structures were a major cause of flow channelling that resulted in short-circuiting the flow path. Such channelling was apparent in all three systems studied resulting in a one third reduction of the flow path at Bartram and Hird systems. It is recommended that the use of culverts or trenches as cell connectors be avoided. Where constraints exist that necessitate culverts, forebays should be designed to reduce the channelling effect into the cell.

A feature of wastewater wetlands is the use of diffuser structures at the inlet. This practice is rarely employed in stormwater treatment and was not present at any of the study sites. However, were that design strategy employed the first cell of the system could be more effective in contaminant removal rather than acting as the diffuser unit. The total substrate store in the first cell of the study sites was the least of each respective system. This was not just a function of the smaller areas involved but was reflected in the low  $\text{g/m}^2$  of the mineral substrates at Hird Road and Russell Street. The diffuser system can either be a mechanical structure or a short forebay flowing to a shallow, and densely vegetated area via swale drains.

Short-circuiting potential occurs where the flow path is reduced in width, either by constrictive connections such as culverts, basin design that funnels the flow, or internal patterns that provide a path of least resistance. It is recommended that once the stormwater has entered the wetland system design must ensure that the flow path is not constricted in any way. This will not only remove short-circuiting potential but promote a plug flow regime.

Outlet structures at all study sites were constrictive and controlled discharge, as is recommended in literature (Hammer & Knight, 1992). However, findings of the nutrient retention studies suggest that outlets should have filters that can trap particulate matter generated by the wetland system.. Current design trend is to locate open water areas immediately prior to discharge structure. This was the case at Bartram and Russell wetlands whereas at Hird the discharge ditch was located at one end of the expanse of open water forming the natural wetland. This encourages channel flow to the outlet and increases the potential for particulate transport exporting pollutants from the wetland system. Ideally, the discharge

cell should be densely vegetated with swale drains directing the discharge flow to an outlet structure. Such a structure will reduce the transport load potential of discharge waters.

Vegetation as a design tool and nutrient store is under-rated in the belief that the seasonal cycles of wetland vegetation render it a short term store and as such of little value to long term performance objectives. This is a narrow view of the role of vegetation in wetland systems. Dense reed beds control flow, act as sediment traps, provide nutrient removal functions through biological uptake and transformation within their rhizosphere, increase the organic content of surrounding substrates and provide a significant nutrient store (Guntenspergen et al., 1989; Meney, 1994). The significance of vegetation as a nutrient store was apparent in the total store determination at both Bartram and Hird Road systems. Design techniques as discussed above would stop the export of decaying plant matter from the system. This study did not determine a preference for species but nutrient store analysis demonstrates the increased storage capacity of dense emergent reed beds over fringing vegetation. This was particularly evident in the major cells in the Bartram system. Although not conclusive, the findings of the nutrient store study suggest a role for floating vegetation in nutrient removal. Design would need to incorporate trapping or screening mechanisms to prevent the downstream transport of floating macrophytes. The increase potential for nutrient removal and storage provided by floating vegetation justifies their inclusion in wetland design considerations.

The high phosphorus  $\text{g/m}^2$  in study examples of soil amelioration (red mud) at Bartram Road was roughly equivalent to that of the peat sediments. Both these soil types demonstrated a higher storage capacity than did the natural mineral sands. Given the observed benefits of soil amelioration in this study it is recommended that future projects research the use of red sand, crushed limestone (Kayallp et al., 1988) or industrial slag (Mann & Bavor, 1993) as a means of increasing nutrient storage and retention capacity in substrates. The problems associated with the use of red mud observed in this and other studies (Sampson, 1994) should exclude that material from consideration for future soil amelioration.

### **Monitoring, Evaluation and Reporting Recommendations**

If only one recommendation of this study was to be implemented, it would be that design incorporates and implements thorough monitoring, evaluation and reporting procedures. Constructed wetland

systems are primarily designed to imitate natural systems. This implies that the constructed system is a dynamic one that will develop and evolve as the system matures. To track the development the system must be monitored.

Without regular structure assessments managers of the respective wetlands are unlikely to know if design inadequacies or alterations to design during construction are contributing to the poor performance. Conversely, evolution of the system may also provide insights in elements generating a more successful performance. The sampling and determination of nutrient stores in substrate and plant pools have two purposes. First, it gives an indication on the fate of pollutants retained by the wetland system. Second, it allows management action on prediction of effective life of wetland systems. The mapping of the study sites highlighted both changes to design and design flaws that reflected the poor performance of the systems. Bartram Road had the most significant changes which effected the flow path and residence time of the wetland. Hird Road had no construction plan and the site mapping highlighted the poor positioning of the cell connection. This reduced the effective size of the natural wetland component by a third. The updating of site information need only be conducted bi-annually providing compliance auditing has been completed.

The study found that common methods of performance evaluation were inadequate. In particular, the use of percentage reduction in concentration between inflow and outflow gave a misleading evaluation of performance. The recommendation of this study is that the reporting method on performance evaluation be summary data on inflow and outflow loads and include load retained. This method will bring to the attention of managers any discrepancies in budgets that may bias performance evaluation. The study also highlighted that groundwater contribution to all wetland sites was not quantified and as such it was not known whether it diluted or concentrated surface flows. The groundwater contribution must be quantified allow an accurate performance evaluation.

The daily variation in CRE recorded during this study highlighted the inaccuracy in extrapolating performance from limited data. A consequence of this finding is that the optimum performance evaluation should be on data compiled from sampling on the smallest feasible time scale over an entire seasonal climate period. Very few of the constructed wetlands in the reported literature had extended monitoring periods which could cause some concern over the validity of reported performance.

Performance monitoring represents a significant on-going cost and commitment of resources. Monitoring CRE requires a delicate balance between available resources and performance evaluation on meaningful data. Given that the majority of runoff occurs during July, August and September in Perth it is recommended that as a minimum this period be monitored for performance evaluation. As discussed in Chapter 4, the sampling interval can be effectively extended using dataloggers and auto-samplers. It is recommended that bulked samples originating from refrigerated auto-samplers be collected at a maximum of seven day periods. These periods should be flexible to enable particular flow events to be sampled.

### **Limitations of the Study**

The availability of resources constrained the scope and the depth of the study. The scope of the literature was restricted by the format for professional journal publications limiting the continual reporting of constructed wetland projects. This meant that majority of the literature search was confined to conference papers, seminar presentations, texts and internal trade papers. Thorough reporting of design criteria for constructed wetlands was not common and this highlights the need for an Australian data base similar to that prepared by Knight et al. (1990) on American constructed wetland projects.

The field assessments on flow patterns and nutrient retention were limited by constraints on time, personnel and equipment. However the lack of replication did not significantly detract from the findings of the study. The purpose of the field studies was to investigate the relevance of design elements at each wetland to the performance of the wetland. The success of the study was probably due to significant design inadequacies at each site. Findings from the flow studies demonstrated the necessity to perform such studies, even on a limited basis. Replication of the flow studies in particular would be difficult to achieve. One, there are only a few constructed wetlands in the Perth region and two, the wetland designs are so diverse that site replication would be impossible. However from a management perspective the study revealed the need to replicate flow regime testing within each cell of the wetland and over a variety of flow conditions.

Data collected from the nutrient retention studies will act as baseline data for future assessments at these wetland sites.

## **Conclusion**

Constructed wetlands can effectively remove pollutants from urban stormwater but the success of this strategy is dependent on the application of effective design criteria. Currently, their design is on an ad hoc basis and this is reflected in the inconsistent performance of locally constructed wetland projects. Ideally, the constructed wetland projects should be part of an integrated catchment management strategy that aims to reduce the level of pollutants at the source. This is preferable to relying on an end-of-line treatment such as constructed wetlands as the only means of pollution control.

The design problems identified in this study suggest a lack of understanding of the contaminant removal functions of wetlands in that to be effective they cannot be compromised. This problem can be overcome by ensuring project teams incorporate a wide range of disciplines including as a minimum wetland ecologists, hydrologists and engineers.

Implementation of the design modifications recommended at Bartram, Hird and Russell constructed wetland systems would result in significant performance improvement such that they would be classed as successful projects. The potential advantages of treating urban stormwater pollution utilising constructed wetlands are too great to allow set backs experienced by current projects to hinder the development of future constructed wetland projects. It is recommended that the WAWA formalise the design criteria for constructed wetlands and persist with both the research into and the implementation of the strategy.

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